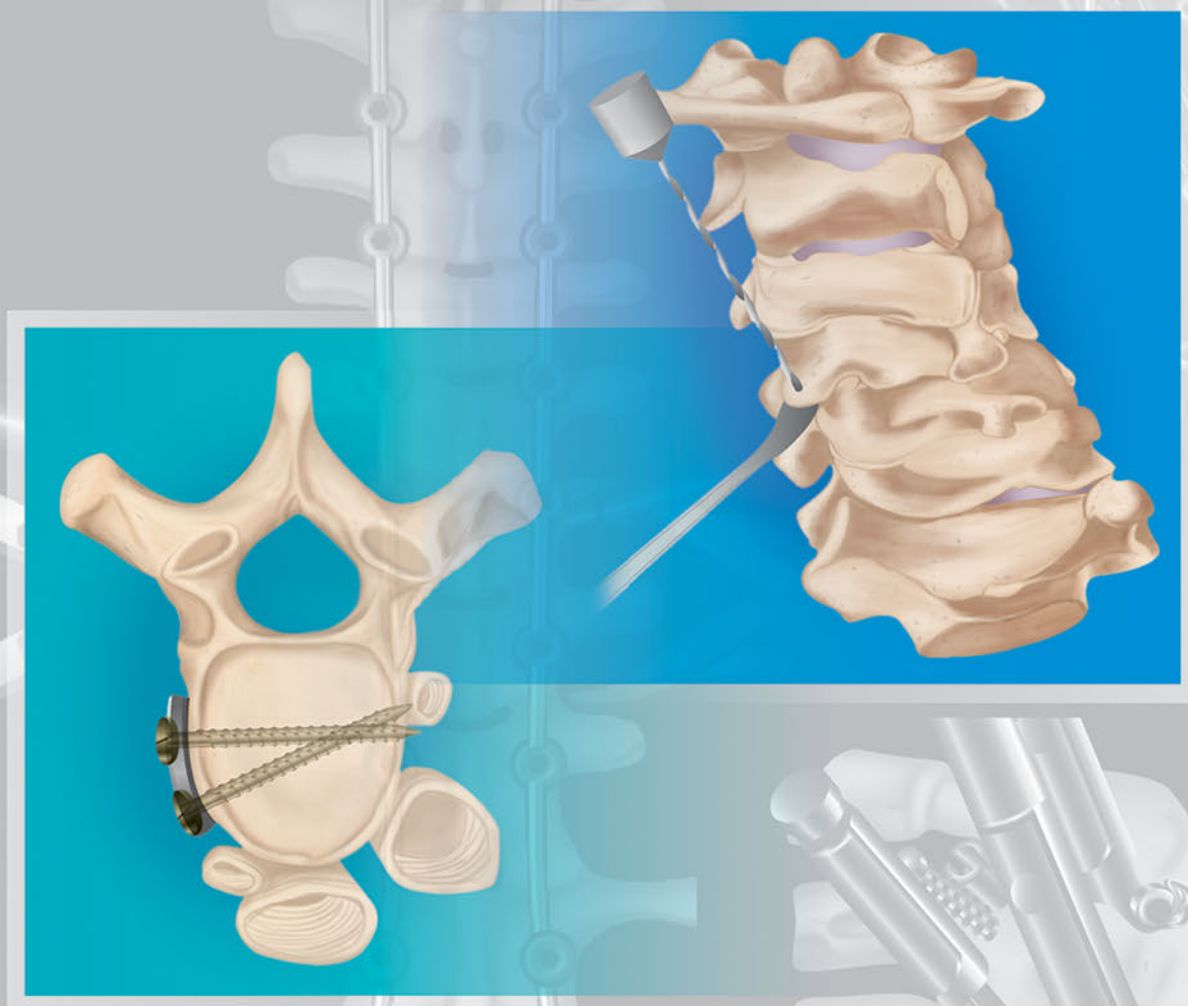
Spine Surgery

Tricks of the Trade

Third Edition

Alexander R. Vaccaro
Todd J. Albert



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Third Edition

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To my family: Barbara, Stuart, Elliot and Emily. You are inspirational to me every day and in every way. Thank you for all your love and support.

Todd J. Albert

The ultimate academic and clinical role model and inspiration for my career is attributable to one of the greatest icons in Orthopaedics, Dr. Richard H. Rothman. For him I have the greatest gratitude and respect.

Alexander R. Vaccaro

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Foreword

In this third edition of *Spine Surgery: Tricks of the Trade*, Dr. Alexander R. Vaccaro and Dr. Todd J. Albert assemble some of the most well-respected spinal surgeons in the world today to produce a virtual bible of tips, suggestions, and solutions for almost any conceivable spinal surgical procedure.

Through the finely edited chapters—including 30 new topics in this edition, all with a consistent outline of presentation that makes absorbing the details smooth and easy—the authors describe the pearls and wisdom that only come by practicing spinal surgery over an extensive period of time. This type of information is invaluable, for it is not necessarily presented at the many societal and training meetings that spinal surgeons attend where it may be seen as "too esoteric" or "non-scientific." However, knowledge of these tips and tricks can often mean the difference between a successful surgery and one that goes technically awry with increased difficulty and greater potential for untoward complications.

The art and technique involved in the practice of spinal surgery have evolved immensely over the past 20 years with the use of more minimally invasive methods of neural decompression, spinal column realignment and stabilization—up to and including improved open reconstructive deformity techniques allowing often near-complete 3D correction of disabling spinal deformities in a safe manner. This age of renaissance in our field, with contributions from both orthopaedic and neurosurgical spinal surgeons, has increasingly emphasized linking optimal patient outcomes to optimal technical performance during spinal surgery. Who would not want to glean tidbits of knowledge that will make their spinal surgical practice safer and more efficient, with fewer complications? This compilation of expert advice and practical tips provides such information, and that is why I feel that this common-sense advice approach to the craft of spinal surgery should be read by everyone, whether learning or practicing the trade—trainees of all levels as well as junior and even senior attending spinal surgeons will find this book invaluable.

I congratulate Drs. Vaccaro and Albert for taking the time and energy to revamp this highly successful book, and I take comfort in the knowledge that it will promote the further growth in the field of spinal surgery that certifies its reputation as a distinct surgical specialty. This unique book elevates our profession to highlight the many nuances and technical aspects that allow for safe and successful spinal surgery, and it will be standard reading for all involved in the practice of spinal surgery for years to come.

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Preface

Examination of the spine as it pertains to human ailments dates as far back as Ancient Egypt (1500 BCE), when the famed Smith Papyrus recorded the management of fractures and dislocations of the cervical spine. By comparison, the modern day practice of spine surgery can be said to have evolved through advances in medical imaging, beginning with the invention of radiology by Röentgen in the late 1800s, through the advent of computed tomography in the 1960s, to the development of magnetic resonance imaging in the 1980s. Indeed, over the past decades new developments in both technology and technique have propelled forward our ability to help improve the lives of patients with spinal disorders in ways unimagined by previous generations of surgeons.

In the past decade, the development of minimally invasive procedures in the management of spinal disorders has flourished and continues to transform the landscape of modern day spine surgery. To remain current with this rapidly advancing field, the editors of *Spine Surgery: Tricks of the Trade* have added new and innovative techniques to the third edition of this celebrated series. Once again, we have sought out the most internationally qualified masters of this art, and with their assistance have produced this repository of up-to-date guidance and instruction covering the most popular treatments of the spine.

This third edition has been fully revised and updated, with the addition of thirty new chapters, the majority of which detail procedures which did not exist during the publication of the second edition. As in previous editions, each chapter in this text follows a standard format: (1) a concise description of the procedure and key principles; (2) the expectations of what the surgeon is able to achieve with the procedure; (3) the indications and contraindications for the surgical technique; (4) special considerations and instructions when performing the described surgical procedure; (5) tips, pearls, and lessons learned in order to help minimize any complications or difficulties encountered; (6) key procedural steps; (7) pitfalls associated with the described technique; and (8) available bailout, rescue, and salvage procedures, should they become necessary.

We have found great success with this approachable yet comprehensive format, which allows this text to serve as a valuable compendium for a broad range of readers including medical students, residents, spine fellows, pain management specialists, and spine surgeons from an orthopedic and neurosurgical background. We are confident that the new edition of this text will continue to serve a valuable role in the ongoing education of students and practitioners in this great field.

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Section I

Posterior Cervical Decompression

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I

1 Suboccipital Decompression for Chiari I Malformation

Karl Balsara, Kim Williams, Jr., Joshua Heller, and Ashwini D. Sharan

1.1 Description

In a Chiari I malformation, descent of the cerebellar tonsils (> 5 mm below the plane of the foramen magnum) creates a relative obstruction in cerebrospinal fluid (CSF) flow at the occipitocervical junction and can result in signs and symptoms of cervicomedullary compression as well as syrinx formation. Surgical decompression of the occipitocervical junction can reverse this process.

1.2 Key Principles

The surgeon must identify and decompress all structures potentially restricting CSF flow at the occipitocervical junction including bone, fibrous tension bands, dura, arachnoid adhesions, or the cerebellar tonsils themselves.

1.3 Expectations

The goal is restoration of CSF flow and/or reduction in spinal cord syrinx volumes and pressures in most patients. Additionally, a reduction in duration and/or severity of occipital headaches and signs and symptoms of cervicomedullary compression can be expected.

1.4 Indications

A suboccipital decompression is indicated in the presence of a symptomatic Chiari I maklformation. In this malformation, descent of the cerebellar tonsils into and through the foramen magnum causes obstruction of the normal flow patterns of CSF. This most frequently presents with occipital headaches that are worsened with Valsalva maneuvers. Other symptoms attributable to the compression of the cerebellum and/or brainstem including cranial nerve dysfunction may occur. The presence, size, or progression of a syrinx may also be an indication for decompression.

Descent of the cerebellar tonsils can also be observed in an asymptomatic patient; the patient should be observed with surgical treatment reserved until symptoms subsequently develop. Aside from the medical management of headache symptoms, there are no nonsurgical alternatives to treatment.

1.5 Contraindications

If the patient has elevated intracranial pressure, this condition should be resolved first.

1.6 Special Considerations

In cases of patients with cranial nerve dysfunction coupled with skull base abnormalities, suboccipital decompression alone may not be sufficient to relieve pressure and an anterior decompression with posterior stabilization can be considered.

1.7 Special Instructions, Positioning, and Anesthesia

The patient should be positioned prone on a standard operating room table with chest rolls in place, knees flexed in the reverse Trendelenburg orientation. The head is positioned in slight capital flexion and fixed in place by a Mayfield head clamp to facilitate positioning and to allow anesthesia access to the head.

1.8 Tips, Pearls, and Lessons Learned

Sufficient flexion is important for adequate exposure and safe decompression, particularly at the base of the foramen magnum.

1.9 Difficulties Encountered

Carefully inspect the preoperative magnetic resonance image (MRI) for the presence of a venous sinus in the area of durotomy. It is not uncommon to find a straight sinus descending from the torcula or a circular sinus at the base of the foramen magnum, especially in pediatric patients.

1.10 Key Procedural Steps

Once positioned, prepped, and draped, a midline incision is performed from the inion to the top of the C2 vertebral body (see **Video 1.1**). A width of 1 to 1.5 cm of C1 should be exposed lateral to midline. The width of the exposure of the subocciput must be sufficient to decompress the entirety of the tonsils. A laminectomy of C1 may then be performed with a bur and/or rongeur.

Next, address the suboccipital craniectomy. Typically, the removal of 3 cm superior and lateral to the foramen magnum at midline is sufficient to adequately decompress the cerebellar tonsils. Be aware of the extra thickness of bone in the midline and at the base of the foramen magnum. Also be alert for a dense adhesion between the dura and the base of the foramen, which should be removed to improve CSF flow dynamics. Care to avoid a dural tear and subsequent CSF leakage is paramount.

There is debate on whether a bony decompression alone is sufficient to decompress a Chiari malformation. Further options include partial dural splitting, arachnoid sparing dural opening with or without grafting, dissection of the tonsils until the obex is identified and opened, and cautery or resection of the cerebellar tonsils themselves.

Our practice is to open the dura in an arachnoid-sparing fashion. The cerebellar tonsils can then be visualized through the arachnoid. If they appear to be mobile with CSF pulsation, then the dura is directly closed with a graft. If not, then the arachnoid is opened and the tonsils are dissected to the exit of the fourth ventricle.

Opening of the dura is performed through a Y-shaped incision from the corners of the suboccipital exposure. In some cases, a descending or circular venous sinus may be present in the dural leaflets. These can be avoided or ligated as conditions dictate. Carry the durotomy distally to the C1 level, taking care to incise all palpable tension bands in the dura.

Closure of the dura with a graft is recommended to avoid reapproximating the dura under tension. An autograft of pericranium may be obtained through the top of the initial incision, or through a separate incision above the decompression site. Alternatively, a dural substitute can also be used. In either case, a watertight dural closure is important to prevent the formation of a postoperative pseudomeningocele.

1.11 Bailout, Rescue, and Salvage Procedures

In most cases, even if a syrinx is the only symptomatic component of the Chiari presentation, it is advisable to perform the suboccipital decompression first, and reserve direct treatment of the syrinx as secondary. Postoperative assessment by MRI should be performed at 3 to 12 months postoperatively. In some cases, a spinal cord syrinx may not improve or resolve after decompression. The surgeon should then re-evaluate whether a repeat decompression is indicated or consider a syringosubarachnoid, syringoperitoneal, or syringopleural shunting procedure.

Pitfalls

- The craniectomy must be sufficient to decompress the cerebellar tonsils; however, one that is too large may result in secondary headaches due to sagging of the cerebellum through the craniectomy defect.

2 Cervical Laminectomy and Foraminotomy

Andrew H. Milby, Philip A. Saville, Gregory D. Schroeder, and Harvey E. Smith

2.1 Description

These procedures involve the removal of the posterior aspects of the cervical spine (spinous processes and laminae) to relieve compression on nervous structures caused by cervical spondylosis, disk herniation, tumor, or deformity.

2.2 Key Principles

Symptomatic myelopathy arising in the setting of cervical spinal stenosis presents as progressive spinal cord dysfunction in adults. Posterior cervical decompression via a cervical laminectomy allows for effective decompression of multiple spinal segments. For patients who also present with radicular symptoms, a foraminotomy may be performed independently or together with a laminectomy to decompress the nerve roots as they exit the neural foramina.

2.3 Expectations

A laminectomy may halt the progression of symptomatic spinal cord dysfunction. Due to the risk of subsequent kyphosis, instability, and possible recurrent canal stenosis (postlaminectomy syndrome), posterior instrumented fusion is generally also performed in the setting of a multilevel cervical laminectomy.

2.4 Indications

- Laminectomy: Multilevel cervical stenosis (in the setting of lordosis) due to spondylosis or ossification of the posterior longitudinal ligament
- Foraminotomy: Radicular pain with associated imaging findings of foraminal stenosis or soft foraminal disk herniation
- Preoperative radiographs should be obtained with flexion and extension views to assess overall sagittal alignment and confirm if a neutral or lordotic spinal posture is achieved with extension view. In the setting of a fixed cervical kyphosis, it may not be possible to adequately decompress the spinal cord without corrective osteotomies.
- Magnetic resonance imaging (MRI) should be obtained routinely to assess for the degree of stenosis as well as the presence of abnormal signal in the neural elements. Computed tomography (CT) aids in identifying an ossified posterior longitudinal ligament, an ossified ligamentum flavum, and preoperative planning of instrumentation, particularly if cervical pedicle screws or instrumentation of the upper cervical spine are considerations. A myelogram CT is often obtained if an MRI is not possible because of a ferromagnetic implant.

2.5 Contraindications

- Laminectomy: Fixed kyphotic sagittal alignment
- Foraminotomy: There are no absolute contraindications to a foraminotomy. Care should be taken to consider the degree of stenosis and anticipated magnitude of facet resection if an isolated foraminotomy is considered to avoid iatrogenic motion segment instability or facet fracture.

2.6 Special Considerations

In patients with severe stenosis, care must be taken to avoid insertion of instruments into the stenotic canal. When fusion with instrumentation is indicated, preparations for screws may be performed prior to a laminectomy to reduce risk to the neural elements.

2.7 Special Instructions, Positioning, and Anesthesia

The patient with symptomatic cervical myelopathy in the setting of spinal cord compression is in neurophysiologic extremis. Careful preoperative consideration of intubation method, maintenance of perfusion pressures during anesthesia, and consideration of neurophysiologic monitoring are essential. We routinely utilize both somatosensory and motor evoked potential monitoring when performing decompression of a myelopathic cervical spine; there are clinical practice and regional variations with respect to the use of monitoring.

The patient is positioned prone on either a Jackson table or regular table with chest rolls and a Mayfield holder (▶ Fig. 2.1). We prefer to utilize a Mayfield as it facilitates positioning without contact to the face/orbits. With prone positioning, the patient should be placed in a reverse Trendelenburg position to elevate the head and neck above the level of the heart, thereby decreasing the amount of venous bleeding during the exposure. The knees should be slightly flexed, and the arms tucked at the side with the shoulders taped. The legs should be placed in 30 to 45 degrees of flexion with appropriate padding to minimize risk of injury to the peroneal nerve at the fibular head. Baseline

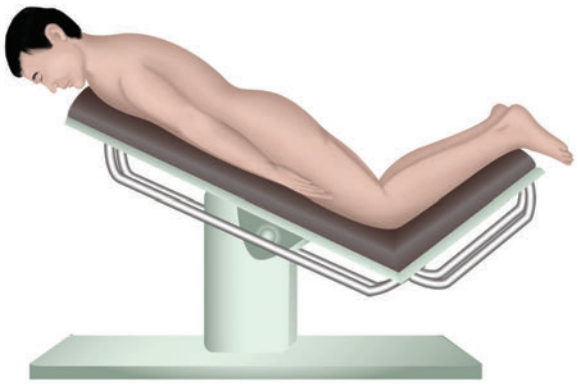

Fig. 2.1 Prone positioning utilizing a Mayfield head holder in reverse Trendelenburg with the knees in flexion.

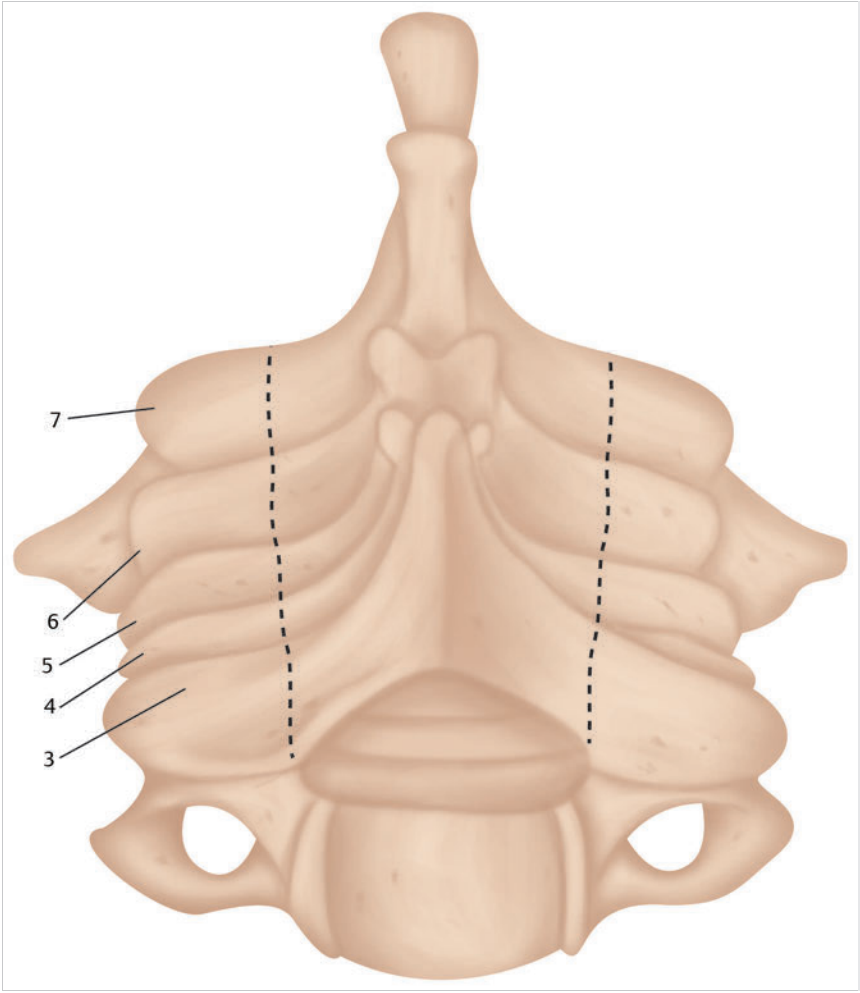

Fig. 2.2 Dashed line indicating the proper location of the laminectomy trough at the lamina–facet border.

and postpositioning baseline neurophysiologic monitoring profiles are obtained. Throughout the procedure, mean arterial pressures are monitored and maintained above 80 mm Hg. Preoperatively many surgeons will consider administration of steroids at the start of the case (i.e., dexamethasone 10 mg).

2.8 Tips, Pearls, and Lessons Learned

Posterior skin folds can present a challenge in some patients after positioning. After securing the spine in appropriate alignment with the Mayfield, the occipitocervical junction may be flexed by tucking the chin; this will greatly facilitate exposure in larger patients.

2.9 Difficulties Encountered

In the event there is a change in neuromonitoring signals after the patient is turned prone, perfusion pressures must be evaluated as a possible cause. If signals are significantly changed during positioning, anterior cord compression may be present necessitating transfer back to the supine position on a stretcher. If signals are position-dependent, it may be necessary to consider an anterior decompression prior to proceeding with a posterior procedure.

2.10 Key Procedural Steps

2.10.1 Exposure

After sterile preparation and draping, the skin is incised down to subcutaneous tissue. Superficial retractors are placed and tension applied over the entire wound while dissecting down to the level of the deep fascia. Application of tension during dissection with electrocautery will facilitate identification of the avascular plane down to the level of the spinous processes. Inadvertent dissection into the paraspinal muscles can result in bleeding. The paraspinal muscles are carefully dissected from the posterior elements in subperiosteal fashion and deep cerebellar retractors are placed. Dissection is carried out to just lateral to the lamina, lateral mass junction. Care must be taken not to disrupt the facet capsules. Note that partial dissection of the muscles from the C2 spinous process may be necessary to completely expose C3, although this should be minimized if C2 is not included in the decompression. The attachments of the obliquus capitis minor and rectus capitis posterior major to the spinous process of C2 should be maintained. Intraoperative imaging must be performed to confirm appropriate level of spinal exposure.

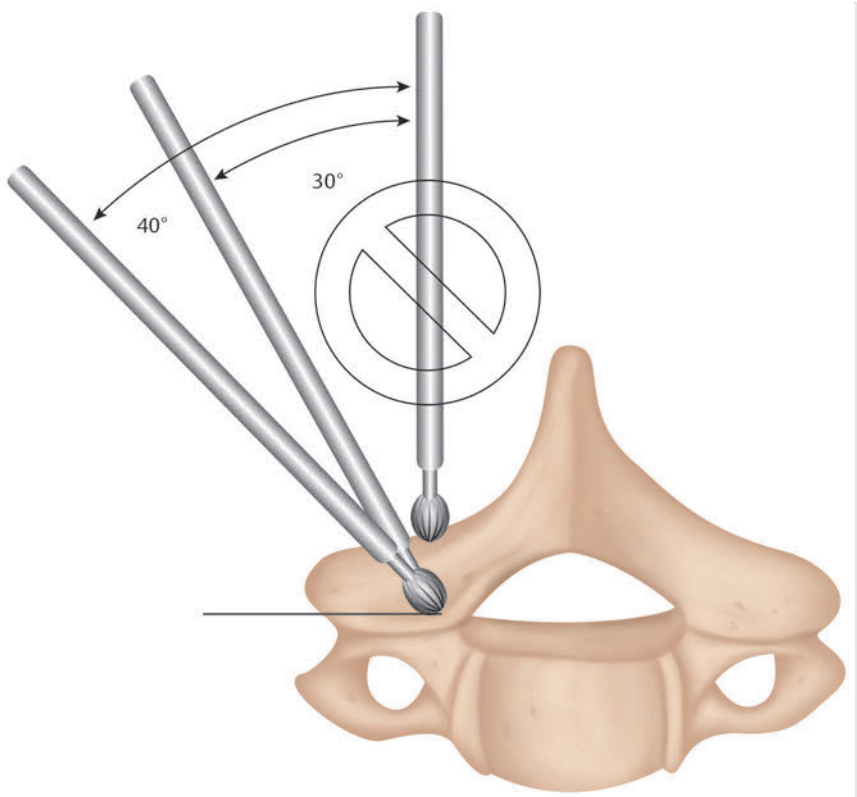

Fig. 2.3 Proper trajectory of the bur approximately 30 to 45 degrees from parallel to the spinous process and perpendicular to the cortices of the lamina.

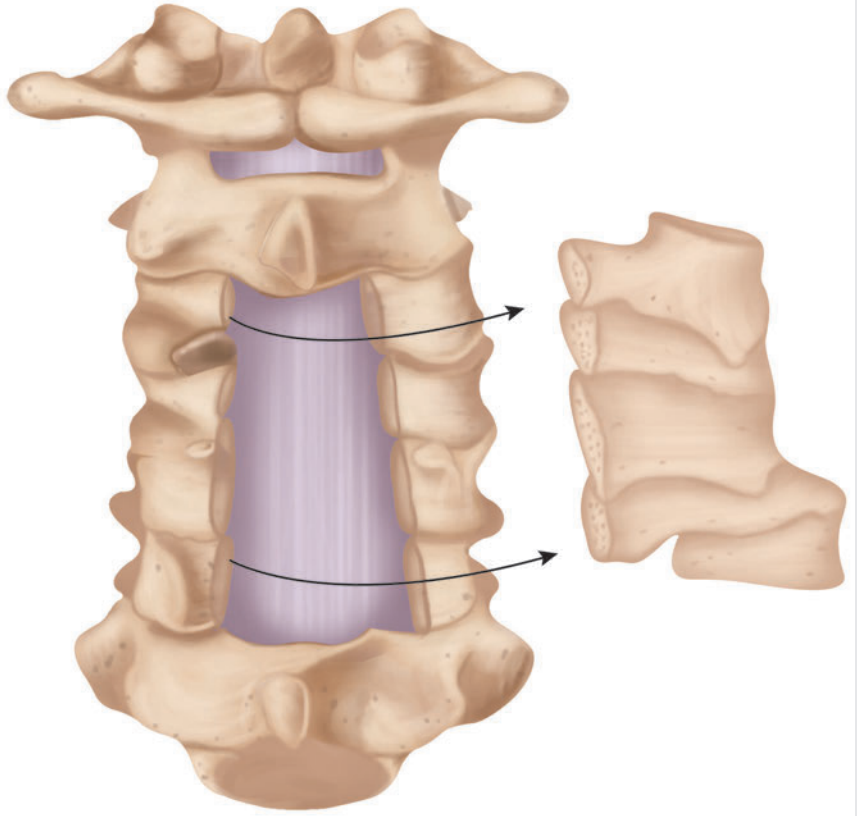

Fig. 2.4 En bloc removal of the lamina following completion of interspinous ligament resection and laminectomy troughs.

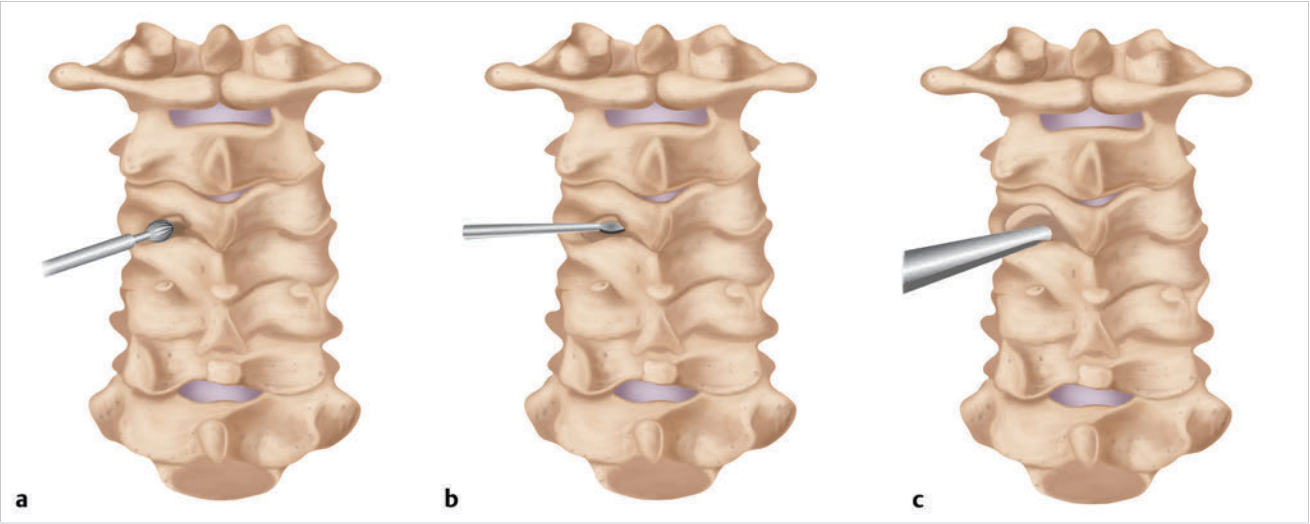

Fig. 2.5 Foraminotomy performed by removal of the lamina and the medial margin of the inferior articular process of the cephalad vertebra. **(a)** A high-speed bur, **(b)** a fine curette, or (**c**) a Kerrison rongeur can be used to remove any processes compressing the nerve root.

2.10.2 Decompression

A rongeur is utilized to remove the interspinous ligament at the bordering cephalad and caudal levels. The spinous processes are then secured with towel clips, and a laminectomy trough is created with a high-speed bur at the lamina–facet border (▶ Fig. 2.2). The bur should be oriented approximately 30 to 45 degrees from parallel to the spinous process so that it remains perpendicular to the cortices of the lamina (▶ Fig. 2.3). The trough is made bilaterally to the level of the inner cortex. The inner cortex is then removed with either a 1-mm Kerrison rongeur or small cervical curette, exposing the ligamentum flavum. The ligamentum flavum is then incised with a 1-mm Kerrison rongeur, while the operative assistant holds the spinous processes via towel clips. The posterior lamina is then removed en bloc (▶ Fig. 2.4). Additional bone resection may be performed with 1- and 2-mm Kerrison rongeurs as necessary.

Decompression of a given cervical nerve root (foraminotomy) requires only a unilateral exposure. After visualization of the facet joint, a portion of the lamina and the medial margin of the inferior articular process of the cephalad vertebra are removed with a high-speed bur (▶ Fig. 2.5a). The removal of the ligamentum flavum should reveal any osteophytes associated with the superior articular process of the caudal vertebra. A fine curette or Kerrison rongeur can be used to remove any processes compressing the nerve root (▶ Fig. 2.5b,c). A blunt hook is used to ensure adequate decompression, taking care to palpate the pedicle and entry zone of the foramen.

2.11 Bailout, Rescue, and Salvage Procedures

- When performing a posterior laminectomy for myelopathy, it is critical to achieve a neutral or lordotic cervical spine. If this is not possible with a posterior laminectomy and fusion alone, either an anterior approach or a posterior osteotomy is required.
- If the thecal sac is compressed by C2 after a C3 laminectomy, often a dome osteotomy (removal of the ventral portion of the C2 lamina) may be performed.
- Posterior foraminotomies for patients with significant cervical radiculopathy can be challenging, especially in the setting of a calcified disk or a disk–osteophyte complex. If a complete foraminal decompression cannot be done without manipulation of the spinal cord, the remainder of the posterior procedure should be completed, and the foraminal decompression should be accomplished from the anterior approach.

Pitfalls

- An excessively wide laminectomy trough can increase epidural bleeding, whereas a trough that is too narrow will necessitate significant additional bone removal. A trough width of 16 to 18 mm can be measured with a paper ruler at each level and scored with bur or cautery prior to decompression.
- Prior to creation of the laminectomy troughs, take care to completely remove the interspinous ligaments and ligamentum flavum at the bordering levels. After completion of the troughs, the spinous processes and lamina are “floating” on the dura and removal of the bordering ligamentum or interspinous ligaments at this point risks inadvertent translation of the lamina against the neural elements.
- Meticulous wound closure is crucial: The nuchal fascia must be carefully approximated, and consideration should also be given to deeper sutures to reapproximate the muscle. A subfascial drain is frequently used.

3 Laminoplasty

Jeremy S. Smith and Mark J. Spoonamore

3.1 Description

Laminoplasty is a commonly used technique to achieve wide posterior decompression of the cervical spinal cord. It is used to address multilevel compressive pathology and may avoid morbidities associated with other anterior and posterior techniques. It permits wide decompression and preserves cervical motion, alignment, and stability.

3.2 Key Principles

Problems with postlaminectomy kyphosis prompted the development of techniques to preserve postdecompression alignment and stability. Laminoplasty preserves the major posterior elements while still allowing for thorough decompression. Because of the decompression from anterior compressive pathology relies on posterior drift of the spinal cord, the procedure must be reserved for patients with a neutral or lordotic alignment.

3.3 Expectations

In the setting of cervical spinal cord compression, laminoplasty can be expected to increase the space available for the spinal cord. Patients with clinical symptoms of cervical myelopathy can expect that laminoplasty will arrest neurologic deterioration and prevent further disability. Outcomes data suggest long-term satisfactory outcomes similar to other cervical decompressive techniques. Patients require minimal to no postoperative immobilization with no concern for pseudarthrosis and adjacent level disease.

3.4 Indications

Laminoplasty is indicated in patients requiring posterior decompression of the cervical spinal cord. The most common indications include congenital spinal stenosis, cervical spondylosis, ossification of the posterior longitudinal ligament, or a combination of the above.

3.5 Contraindications

Laminoplasty should not be performed in patients with a fixed kyphotic deformity as this alignment does not allow for adequate spinal cord drift from anterior compressive pathology. Kyphosis up to 10 degrees, however, has been shown in the literature to be acceptable. Other contraindications include ossification of the ligamentum flavum, previous posterior surgery, epidural fibrosis, or severe cervical instability (e.g., rheumatoid arthritis, spondyloarthropathy).

3.6 Special Considerations

Patient selection is crucial prior to undergoing cervical laminoplasty. The appropriate preoperative planning includes plain radiographs with flexion extension views, magnetic resonance imaging (MRI) and at times computed tomography (CT) with reconstructions. The workup is performed to determine the overall alignment, presence or absence of instability, the appropriate levels to be decompressed, and the appropriate side and position of the gutters. Any aberrant anatomy should be identified and the surgical plan tailored accordingly (▶ Fig. 3.1).

3.7 Special Instructions, Positioning, and Anesthesia

The patient is positioned prone using the Mayfield pin headrest. The alignment is in a slightly flexed position to limit overlap of adjacent lamina and allow for easier exposure. The arms are tucked and shoulders taped to improve radiographic visualization of spinal landmarks. The bed is placed in 20 degrees of reverse Trendelenburg to decrease intraoperative bleeding and improve visualization of the surgical field. Baseline and postpositioning spinal cord monitoring (motor evoked potentials, somatosensory-evoked potentials) should be obtained. The appropriate anesthetic should be coordinated between the anesthesiologist and spinal cord monitoring technician to ensure proper monitoring. In patients with cervical myelopathy, arterial line monitoring is preferred with a target mean arterial pressure of 80 to 85 mm Hg.

3.8 Tips, Pearls, and Lessons Learned

Adhering to a midline approach through intermuscular plane and subperiosteal dissection avoids excessive bleeding. Careful attention to avoid damage to facet joint capsules will prevent iatrogenic injury and future degeneration. Dissection laterally should be limited to avoid excessive venous bleeding. The bicortical gutter should be created before the unicortical gutter (▶ Fig. 3.2). The open side of the laminoplasty should be performed where the compressive pathology is most significant. The patient is placed in collar immobilization postoperatively until the wound has healed. Once this is confirmed, active range of motion is encouraged.

3.9 Difficulties Encountered

Difficulties during the procedure usually occur at the opening side of the laminoplasty. If there is difficulty opening the "door," there is likely inadequate bone or ligament resection. Using a nerve hook, gently palpate the patency of the bicortical trough. If bone is felt, carefully revisit the area with the high-speed bur. Bluntly develop a plane between the dura, and carefully resect the laminar bone and ligamentum flavum with a no. 1 Kerrison rongeur. If the open-door-side gutter is completed and there appear to be problems with the hinge side, carefully revisit the unicortical or hinge side with the high-speed bur. Areas most

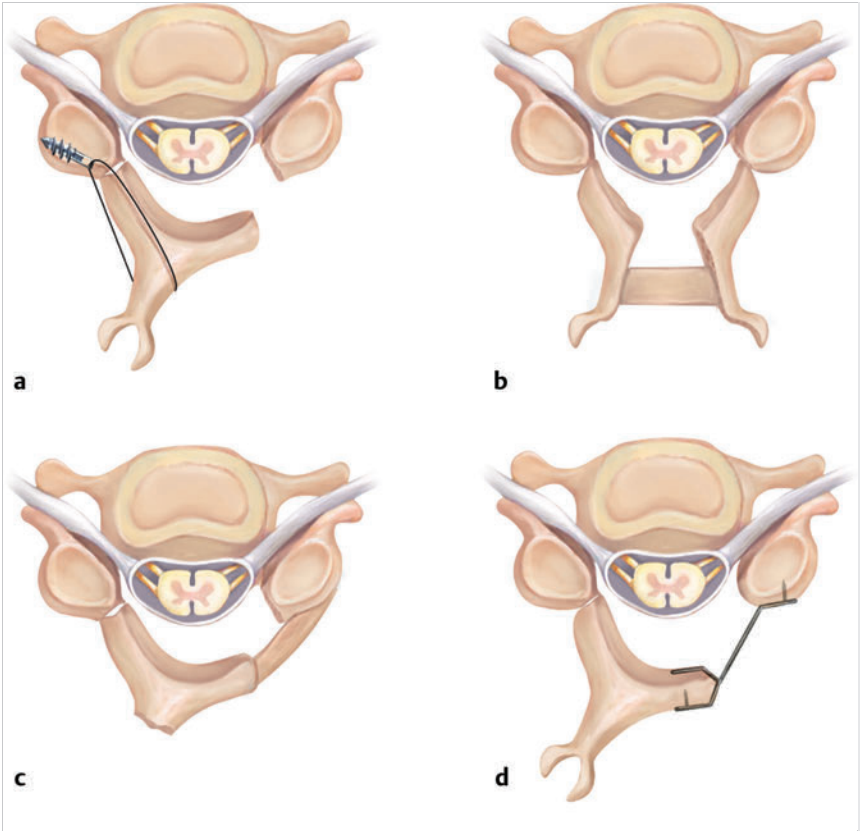

Fig. 3.1 Various methods commonly used for cervical laminoplasty. (**a**) Single-door suture technique. (**b**) Double-door allograft. (**c**) Single-door allograft. **(d)** Single-door plate fixation.

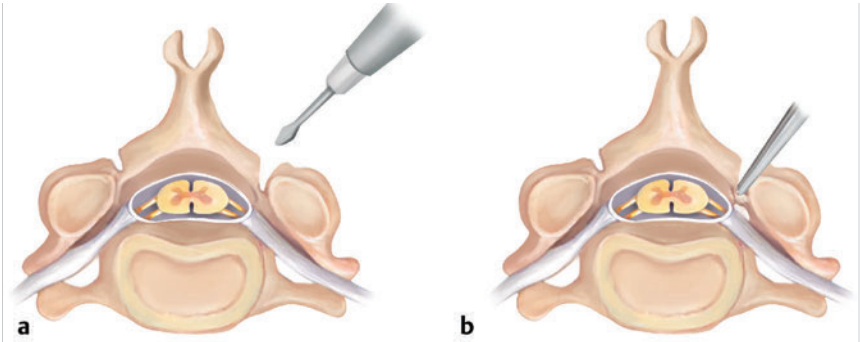

Fig. 3.2 Cross sectional view of (**a**) bilateral troughs being created; (**b**) sublaminar soft tissue structures cut.

commonly missed on the first pass include the cephalad portion of the lower level laminas that remain covered because of the shingling effect.

The most cephalad and caudal levels of the laminoplasty commonly block the doors of the laminoplasty from opening. One must be careful to not unnecessarily resect interspinous attachments that are preserving stability.

3.10 Key Procedural Steps (Video 3.1)

A midline approach must be vigilantly adhered to in order to limit excessive bleeding. After the nuchal ligaments are incised and the spinous processes are identified, a subperiosteal dissection is carried out over the laminar and lateral mass surfaces with careful attention to avoid iatrogenic injury to the facet joint capsules. A localization radiograph confirms the levels of interest. First, the bicortical trough is created using a high-speed matchstick bur on the side that is most clinically symptomatic or has the most significant radiographic evidence of the compressive pathology. The trough should be created just medial to the junction of the lamina and facet joints. A blunt nerve hook is gently passed through the trough to assess for residual bony attachments and to develop an interval between the ligamentum flavum and dura. A no. 1 Kerrison rongeur is used to cut through all sublaminar soft tissue structures that are inhibiting the lamina from opening (▶ Fig. 3.3). The contralateral unicortical trough is created just lateral to the junction of the lamina and facet joints. Careful attention must be made to not violate the ventral cortical wall on this side. Preoperative CT scans may help estimate the thickness of the bony anatomy at this level. Following trough creation, the laminoplasty doors are opened carefully. A greenstick fracture is created on the unicortical trough side. We prefer a technique that evenly and equally opens the spinal canal space to prevent focal

kinking or drift that may cause spinal cord injury. Towel clips are placed on each of the spinous processes and used to stabilize the opened doors. Lamina spreaders may be used to gently and sequentially open the laminoplasty doors. As the canal space is widened, attention is made to soft tissue adhesions from the dura that might be attached to the ventral laminar surface. These are carefully cut using a small Kerrison to avoid a dural injury. Curettes can be used to apply force to the ventral surface to help elevate the lamina. Alternatively, gentle manual pressure can be applied to the spinous process (▶ Fig. 3.4). Careful attention must be made to avoid recoil of the lamina once it has been separated from the dorsal spinal cord as this can cause a catastrophic neurologic event. At this point, the dorsal spinal cord may bulge out and appear pulsatile indicating adequate decompression. If an allograft or plate is being used, a trial sizer might be appropriate. After the appropriate size plate/allograft is chosen, it is appropriately secured using screw fixation to both the lateral mass and lamina (▶ Fig. 3.5). If a suture anchor technique is utilized, this is done with the anchor being placed on the hinged end of the laminoplasty.

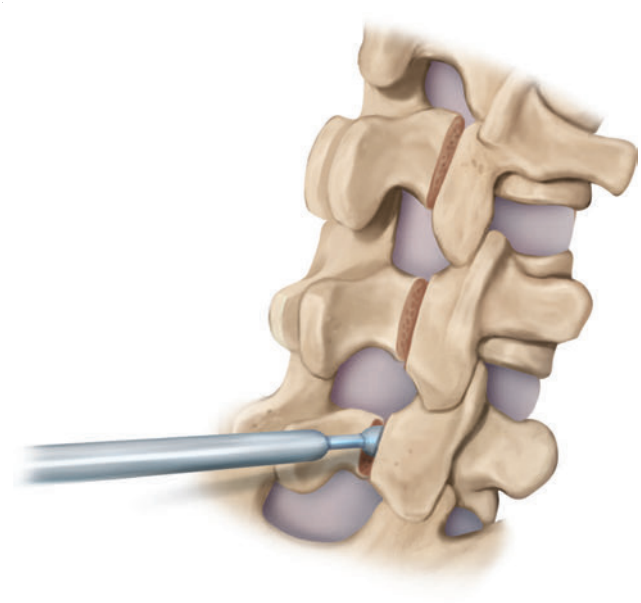

Fig. 3.3 Starting the gutter on the open side

3.11 Bailout, Rescue, and Salvage Procedures

There are a number of reasons that may prevent the hinge from opening. These must be appropriately assessed if this difficulty arises.

1. Ventral cortex on the opening side of the laminoplasty is incompletely resected.

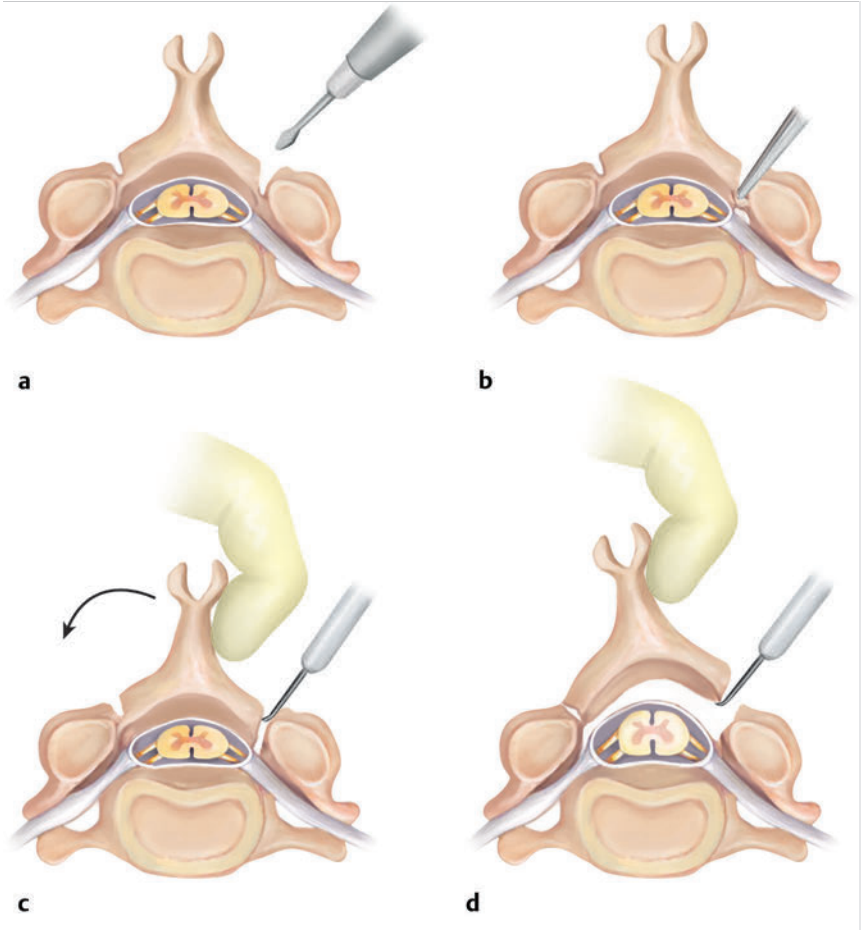

Fig. 3.4 (**a–d**) The gutter is carefully opened manually and with ventral pressure using an angled curette.

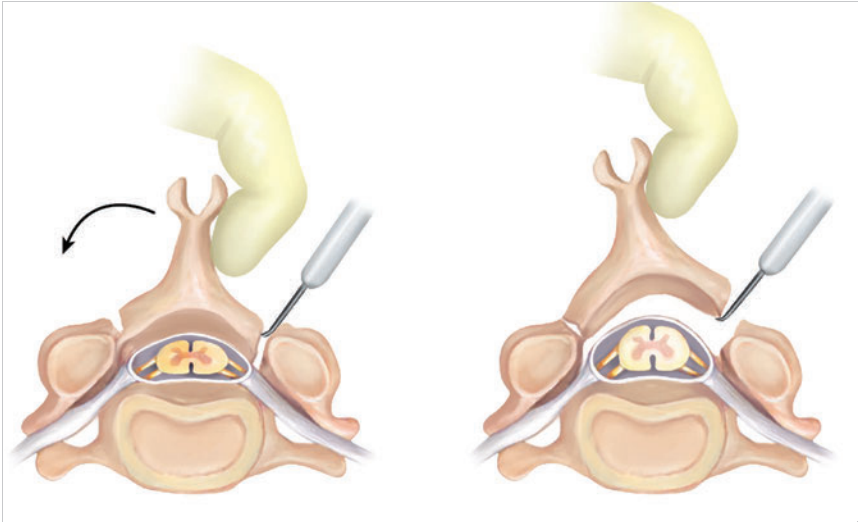

Fig. 3.5 Cross-sectional view after the plate is applied.

2. Remaining ligamentum flavum is tethering the ventral lamina. This occurs most commonly at the cranial or caudal aspect of the laminoplasty.
3. The trough on the hinge side of the laminoplasty is not deep enough.

To prevent a hinge fracture, the bicortical trough is created first. After an initial unicortical trough is drilled on the contralateral side, opening of the trough should be attempted incrementally and carefully. If there is difficulty caused by an inadequate hinge, carefully remove more bone and reassess. In the event of a hinge fracture, various small fragment plates have been designed to secure this fragment and prevent a "floating" fragment from causing spinal cord compression.

If epidural bleeding is encountered, a hemostatic agent can be applied and will be sufficient in most circumstances. Electrocautery should be avoided.

In the rare event that a laminoplasty is unable to be completed (e.g., inability to adequately decompress the spinal canal, multiple hinge fractures, etc.) the option of laminectomy or laminectomy with fusion is available as a salvage technique. The patient must be counseled preoperatively about this potential scenario.

To avoid a postoperative hematoma, subfascial drains are placed prior to closure and removed postoperatively when drainage is at a minimum.

Pitfalls

- Motor palsy: Incidence 5 to 12%, most commonly in the C5 distribution, usually occurs 2 to 3 days postoperatively. The majority resolve over time. Passive range of motion exercises are necessary to preserve shoulder motion.
- Infection: Incidence 3 to 4%
- Closure of laminoplasty with resultant/restenosis: Neurologic recovery is then lessened. Incidence is less when technique involves rigid plate fixation or suture technique.
- Loss of motion/kyphosis: Related to degree of muscle detachment and immobilization postoperatively. Preventative measures include minimizing muscular detachment and encouraging early range of motion with minimal or no collar immobilization.
- Axial neck pain: 40% incidence reported; related to facet joint injury, muscular detachment at C2 and C7, prolonged immobilization, and muscular denervation. Strategies to reduce postoperative neck pain include minimizing muscular detachment particularly at C2 and C7, and early active range of motion with strengthening therapy protocols.
- Hinge fracture: Can be avoided by carefully developing the unicortical trough with incremental attempts at opening the laminoplasty after each decortication with the bur. In the event that a fracture occurs, small fragment plates may be used to stabilize the hinge.

4 Open Reduction of Unilateral and Bilateral Facet Dislocations

Moe R. Lim and Alexander R. Vaccaro

4.1 Description

This procedure provides open posterior reduction of unilateral or bilateral facet fracture/dislocations.

4.2 Key Principles

The key principle for achieving reduction is the gentle re-creation of the injury mechanism followed by manipulation of the affected segments into normal alignment.

4.3 Expectations

- Avoidance of neurologic injury with the reduction maneuver
- Achievement of near-anatomical alignment and stable fusion construct

4.4 Indications

- Unilateral or bilateral facet dislocations or fracture/dislocations that have failed attempted closed reduction
- Unilateral or bilateral facet dislocations or fracture/dislocations that have failed attempted open anterior reduction
- Unilateral or bilateral facet dislocations or fracture/dislocations without evidence of a significant disk herniation on preoperative magnetic resonance imaging (MRI)

4.5 Contraindications

- Hemodynamic instability
- The presence of a significant disk herniation on MRI. Large disk herniations with disk material behind the dislocated vertebral body have the potential to be dragged into the canal during posterior reduction and subsequently compress the cord.

4.6 Special Considerations

After a failed attempt at closed reduction, a cervical spine MRI is mandatory to search for a disk herniation. In the presence of a significant disk herniation, an anterior diskectomy is required prior to open posterior reduction.

4.7 Special Instructions, Positioning, and Anesthesia

Awake fiberoptic intubation avoids excessive cervical extension and further displacement of the fracture/dislocation. Performing the intubation awake allows for the patient to have neuromuscular control of the cervical spine and also allows a neurologic exam after intubation. Neurophysiologic baselines are recorded after the administration of general anesthesia and serially repeated after prone positioning, shoulder taping, and other closed cervical manipulation/positioning maneuvers. Multimodality monitoring is preferred with a combination of motor evoked potentials, somatosensory evoked potentials, and spontaneous electromyogram (EMG) recordings. Extreme caution is used while turning the patient prone to allow for the preservation of cervical stability. Live neurophysiologic spinal cord monitoring with repeated motor evoked potentials during the reduction maneuver is extremely helpful. If an alert is detected, the reduction maneuver can readily be reversed or aborted, potentially avoiding neurologic injury.

4.8 Tips, Pearls, and Lessons Learned

The reduction should be achievable with only gentle manipulation. Greater amounts of force may cause a spinous process fracture or neurologic injury. If difficulty in reduction is encountered, additional muscle relaxation from anesthesia may be necessary. If additional relaxation does not allow safe reduction, the superior articular facet(s) of the caudal vertebra can be trimmed with a bur. This decreases the barrier to posterior translation of the inferior facet of the cephalad level. The amount of bone resected, however, should be minimized to allow native bony stability following the reduction. A nerve hook or curved curette can be used to help gently manipulate the facets and provide additional leverage.

4.9 Difficulties Encountered

If significant neurophysiologic signal changes are encountered during the reduction maneuver, the procedure should be temporarily halted. Because reduction should afford an indirect decompression of the spinal cord, neurophysiologic changes with attempted reduction likely indicate anterior cord compression by a herniated disk. Once other potential causes of the signal changes (such as hypotension) have been ruled out, the patient should be carefully turned supine and an anterior diskectomy performed.

Traumatic dural lacerations may also occur in facet dislocations with a concomitant lamina fracture. Preoperative computed tomography images should be carefully studied to localize the fractured laminae. If spinal fluid leakage is encountered, a watertight repair should be performed. If repair is not possible, a lumbar drain can be used to divert cerebrospinal fluid flow.

4.10 Key Procedural Steps

After prone positioning and establishment of neurophysiologic baseline recordings, a subperiosteal exposure of the posterior

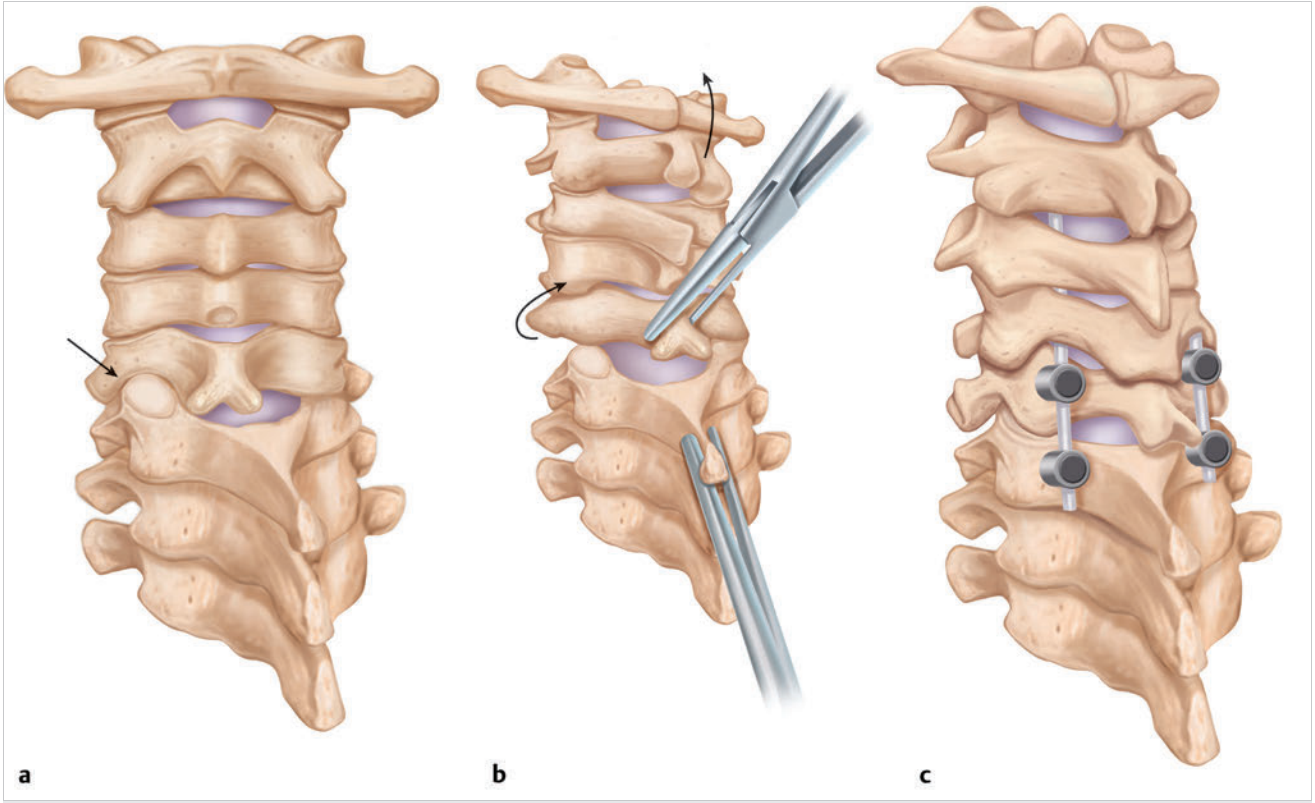

Fig. 4.1 **(a)** The open reduction technique for a unilateral facet dislocation (arrow). (**b**) A gentle rotation, distraction, and kyphotic moment is applied to the cephalad tenaculum to re-create the injury mechanism. (**c**) Posterior compression is applied using spinous process wiring or lateral mass screws.

cervical spine is performed. In case of associated laminar fractures, the preoperative images are studied to avoid inadvertently entering the spinal canal during subperiosteal exposure. Care should be taken to avoid violating the facet capsules and interspinous ligaments of levels not involved in the intended fusion. The dislocated level can often be detected by a step-off in the spinous processes or the associated soft tissue injuries. Once the dislocated levels are identified, the lateral masses are exposed completely. The dislocation can be reduced by grasping the involved cephalad and caudal spinous processes with a tenaculum at the spinolaminar junction. The neurophysiologist should be warned of the possibility of an acute signal change and instructed to serially check motor evoked potentials. If any significant neurophysiologic changes are detected, the procedure should be halted.

Axial caudal traction is applied to the caudal tenaculum. A gentle distraction and kyphotic moment is applied to the cephalad tenaculum to re-create the injury mechanism. A rotational force may also be additionally required for unilateral facet dislocations. The maneuver is applied until the inferior articular processes of the cephalad vertebra are freed from underneath the superior articular processes of the caudal vertebra. Once the inferior facets of the cephalad vertebra clear and become posterior to the superior facets of the caudal vertebra, the difficult portion of the reduction is complete. To achieve anatomical alignment, posterior compression is applied using spinous process wiring or lateral mass screws (▶ Fig. 4.1, ▶ Fig. 4.2, ▶ Fig. 4.3).

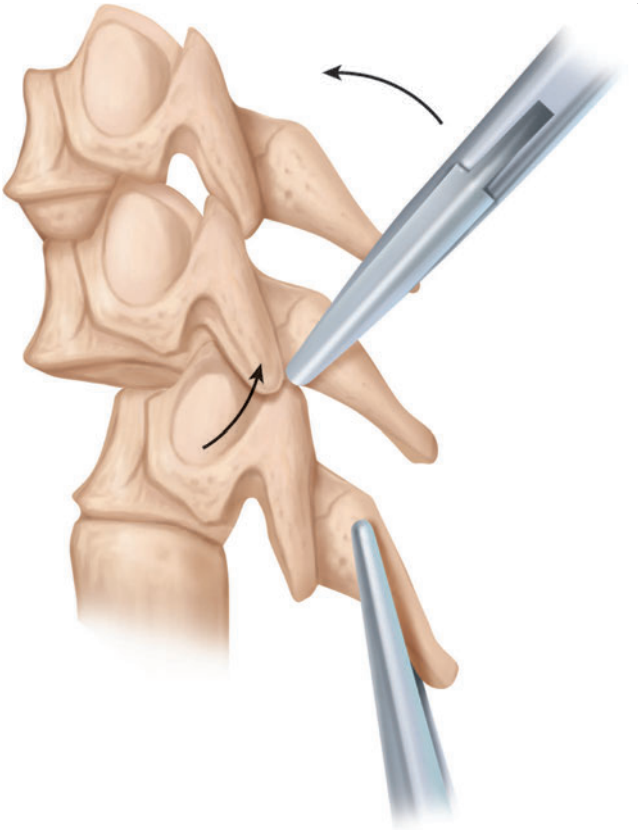

Fig. 4.2 Lateral view of the reduction of the facet joint (arrows indicate traction).

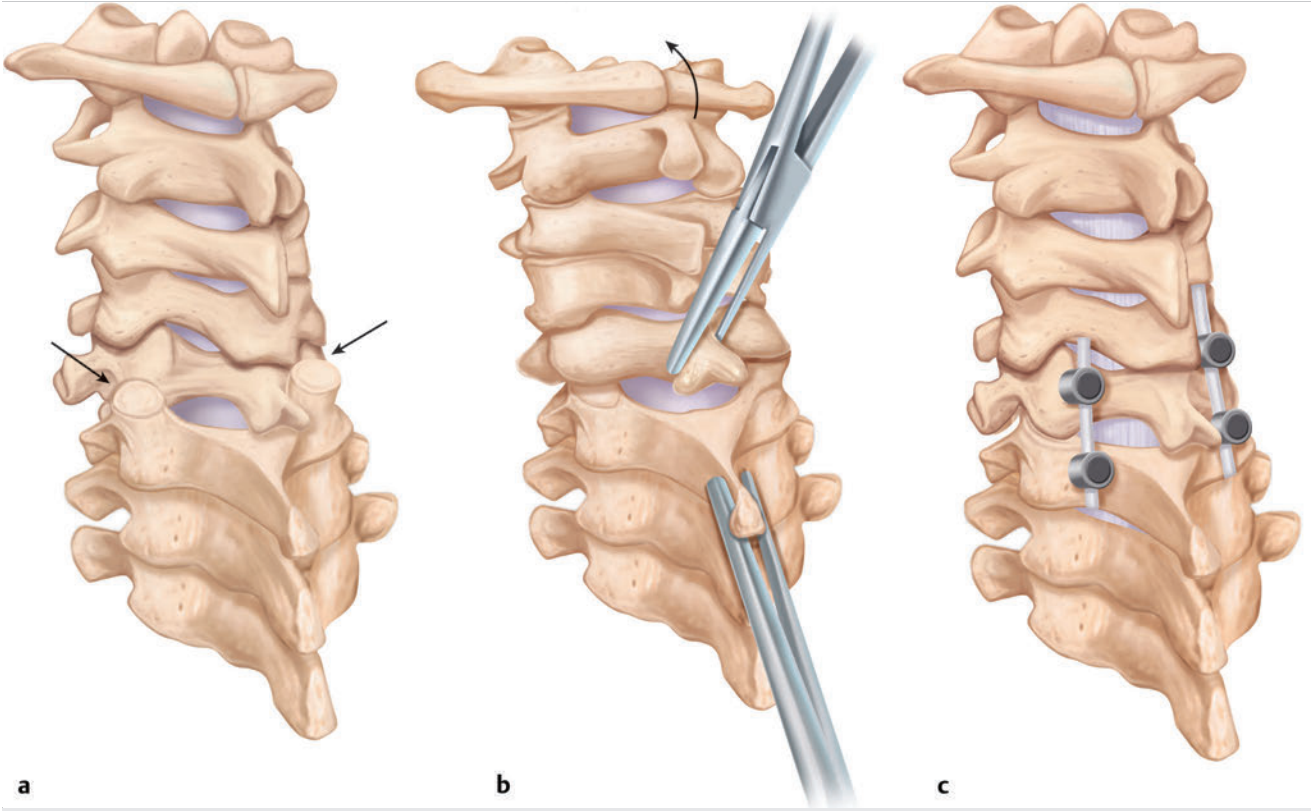

Fig. 4.3 **(a)** The open reduction technique for a bilateral facet dislocation (arrows). (**b**) A gentle distraction and kyphotic moment is applied to the cephalad tenaculum to re-create the injury mechanism. (**c**) Posterior compression is applied using spinous process wiring or lateral mass screws.

4.11 Bailout, Rescue, and Salvage Procedures

In the presence of a lamina or spinous process fracture, manipulation via the spinous process is not possible. In this situation, lateral mass screws can be inserted into the cephalad levels bilaterally. With the screwdrivers still attached to the screws in a fixed angle, the screw–screwdriver construct can be used to manipulate and reduce the dislocated vertebra. With this maneuver, great care must be taken to avoid destruction of the bony purchase of the lateral mass screws.

Pitfalls

- In a severe injury, concomitant lateral mass or facet fractures may limit the degree of inherent stability following reduction of the dislocation. In addition, the use of lateral mass fixation at that site may be prohibited. Should this occur, extension of the stabilization construct or other forms of instrumentation may be warranted.
- In a severe injury, the spine may remain very unstable after the reduction maneuver. If excessive anteriorly directed force is used during preparation or placement of the lateral mass screws into the cephalad segment, the dislocation may recur.

Section II

Posterior Cervical Arthrodesis and Instrumentation

II

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5 Occipital Fixation Techniques

Michael C. Fu, Rafael A. Buerba, Neal G. Haynes, Troy D. Gust, Paul M. Arnold, and Jonathan N. Grauer

5.1 Description

Occipitocervical fixation with midline plate and rod constructs has largely replaced earlier wiring techniques. If significant resection of the robust midline occipital bone is necessary, such as in broad Chiari malformation decompressions, bilateral plating or older wire constructs may be a backup fixation strategy.

5.2 Key Principles

Fixation to the occiput is an important technique for stabilizing the occipitocervical junction for a variety of indications. Surgeons should be mindful of determining the areas of optimal bone stock for instrumentation, avoiding vital neurovascular structures, and achieving the appropriate occipitocervical alignment.

5.3 Expectations

Occipital fixation allows for secure control of the occiput that can then be joined to cervical instrumentation to stabilize the occipitocervical junction. The occiput has significant bone in the posterior midline that can be utilized for such fixation. Given the high degree of motion at the occipitocervical junction, however, long-term stability in this area is dependent on biologic fusion.

5.4 Indications

- Occipitocervical instability related to trauma
- Rheumatoid arthritis or other inflammatory and/or degenerative processes
- Neoplasm
- Congenital anomalies
- Iatrogenic instability related to decompression

Of note, instrumentation and fusion to the occiput is always a viable bail-out procedure for upper cervical stabilization if fixation to C1 is not possible with other techniques.

5.5 Contraindications

- Active infection
- Severe osteoporosis

5.6 Special Considerations

Understanding the cervical spine pathology necessitating occipitocervical fusion is essential. In addition to magnetic resonance imaging (MRI) which is used to delineate the primary pathology, preoperative computed tomography (CT) is generally obtained to characterize the vascular anatomy. The patient should also receive specific counseling regarding the anticipated loss of motion following occipitocervical fixation.

5.7 Special Instructions, Positioning, and Anesthesia

A Mayfield head holder is placed with the patient in the prone position. Occipitocervical alignment can then be optimized using fluoroscopy or plain radiographs.

Neuromonitoring is generally recommended for these procedures. Depending on the specific pathology being addressed, preflip baselines are often worth checking as many of these patients have significant instability, stenosis, and/or neurologic deficit.

5.8 Tips, Pearls, and Lessons Learned

A neutral head position should be the goal in preoperative positioning. With that said, if there is uncertainty in the exact position of flexion or extension, slight flexion is generally preferred. This is because the postoperative patient will intuitively bring his or her head to neutral alignment by lifting his or her head for forward gaze, which will help restore cervical lordosis. On the other hand, if fixation was performed in extension, kyphosis will be imparted on the remaining mobile cervical segments as the head is brought down for forward gaze.

The most superior part of the plate should be placed just below the inion (external occipital protuberance). A bur may be used just below this bony prominence to flatten the contour (▶ Fig. 5.1, **Video 5.1**). This provides an easy landmark and facilitates appropriate seating of the plate.

The occipital bone is significantly thicker in the midline; thus, midline screws allow for the greatest fixation. If placing bicortical screws, a safe technique is to begin drilling at relatively shorter depths, around 6 to 8 mm, and increase at 2-mm increments if bone can still be felt at the base of the hole with a probe (▶ Fig. 5.2). Once bone can no longer be felt, the bicortical screw can then be inserted. It should be noted, however, that unicortical midline occipital screws have been shown to have equivalent pull-out strength as lateral bicortical screws, although less than bicortical midline screws. If encountered, cerebrospinal fluid (CSF) leakage at this stage can generally be stopped by placing a screw into the hole. Bone wax may also be helpful to prevent CSF leakage.

If there is poor midline purchase, bilateral plates or a modular addition to a midline plate can be considered to allow for fixation points off the midline (▶ Fig. 5.3). For dual plating, three or more occipital screws are generally used on either side of the midline just below the superior nuchal line and as close to the midline as possible.

For wire placement, a malleable rod template can be fashioned with the assistance of fluoroscopy. The rod implant is then bent to match the template. Patience is required during this step to ensure that the rods rest on the occiput and that no

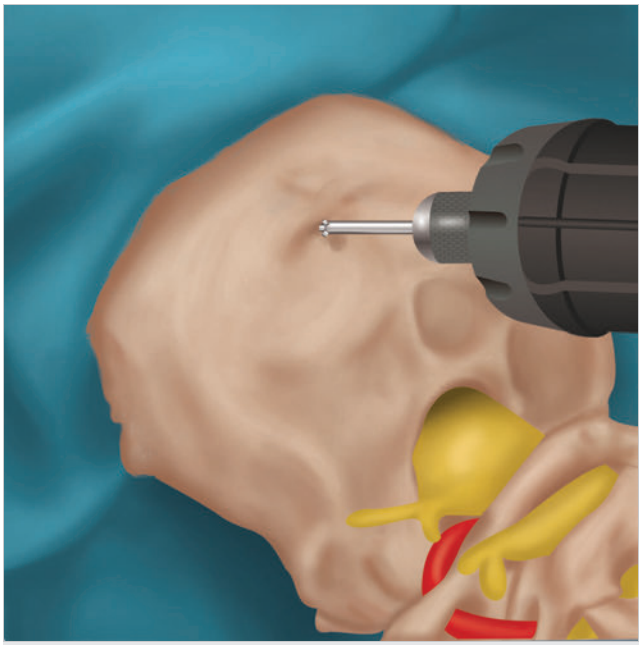

Fig. 5.1 A bur can be used at the external occipital protuberance to create an accommodating contour for a midline occipital plate, while removing as little bone as possible.

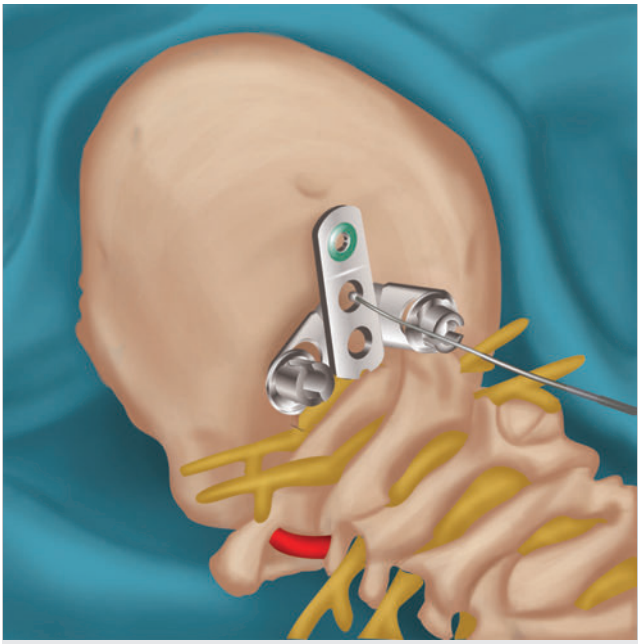

Fig. 5.2 Use of a probe to feel for bone between increasing the drill depth at 2-mm increments will help to safely achieve bicortical screw purchase in the occiput.

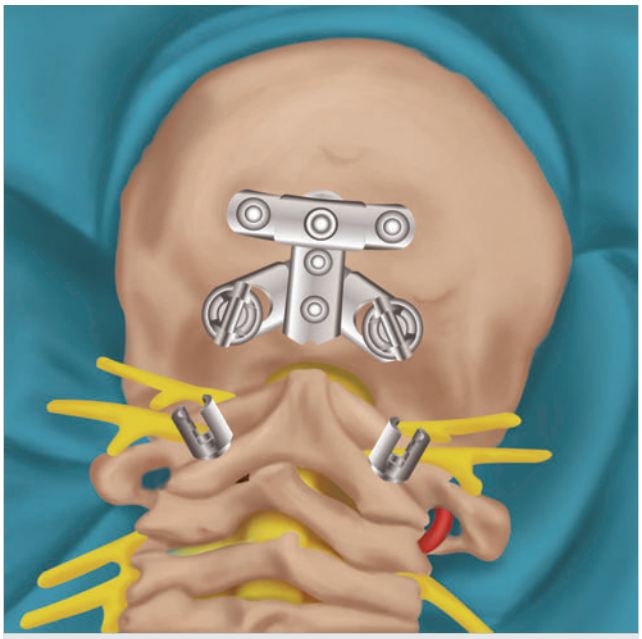

Fig. 5.3 A modular addition to occipital plate allows for placement of lateral screws in case of poor midline screw purchase, or depending on the particular instrumentation system, suboptimal alignment with cervical instrumentation.

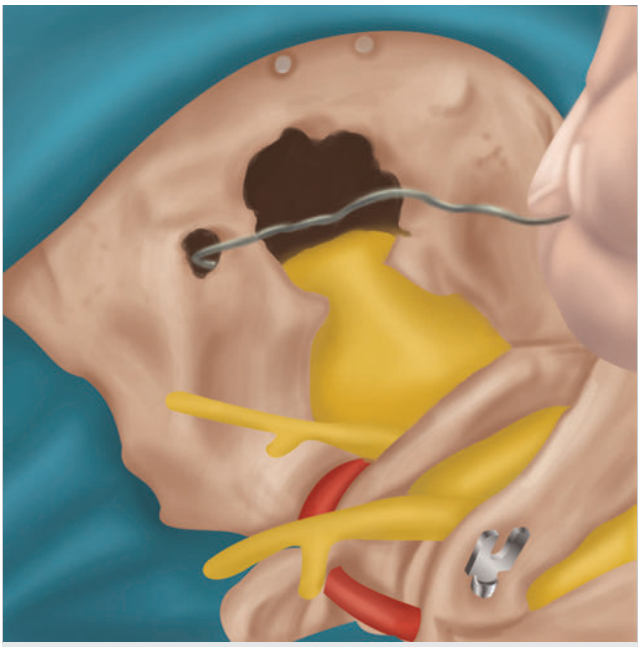

Fig. 5.4 Suboccipital craniectomy with surrounding bur holes enables safe passage of a bent wire tip in cervical wiring.

space exists between the rods and occipital bone, as this can result in the wire cutting through the bone. As this technique is generally considered only in the setting of a suboccipital craniotomy, the bent-tipped wire is passed from an adjacent bur hole into the craniotomy defect (▶ Fig. 5.4).

5.9 Difficulties Encountered

Durotomy and neurovascular injury can occur during drilling, screw placement, wire passage, or suboccipital craniotomy. Additionally, there is a risk of vigorous venous bleeding caused by transverse dural sinus injury if drill placement is too superior. When a durotomy occurs, resulting CSF leakage can usually

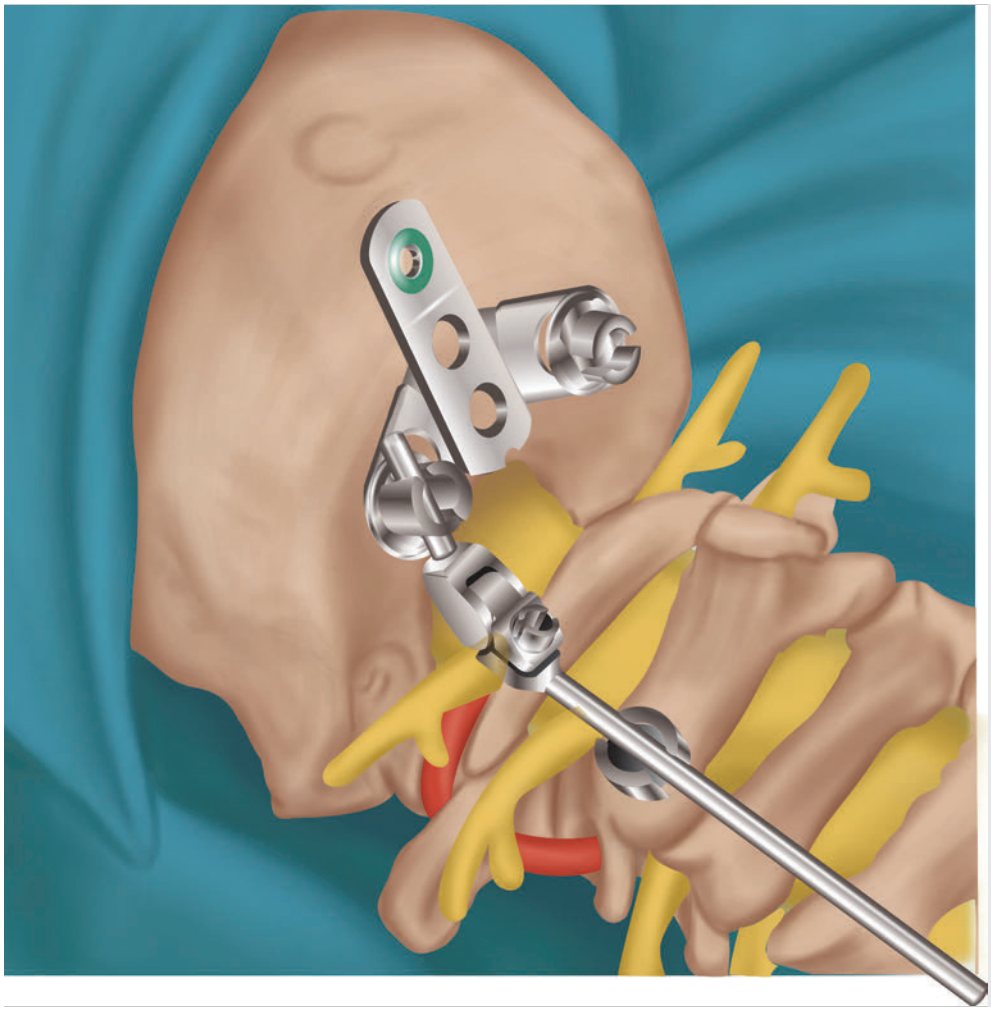

Fig. 5.5 Hinged rods may be used in place to single-piece contoured rods to facilitate locking in the occipitocervical fixation in the desired alignment, at the cost of increased hardware bulk and prominence.

be stopped by placing the screw into the hole. Similarly, if dural venous sinus is encountered during drilling, immediately place a screw and do not attempt a repair. If a screw cannot be placed, plugging the drill hole with bone wax is an acceptable alternative. Postoperatively, when a screw is confirmed to be in the sinus, antiplatelet therapy should be considered as prophylaxis against dural venous thrombosis. A high index of suspicion for potential subdural hematoma development must be kept in mind.

5.10 Key Procedural Steps

Patient positioning is key. Unlike constructs that do not extend to the occiput, specific attention clearly needs to be paid to the position of the head relative to the cervical spine. This should be confirmed with fluoroscopy. Exposure is then carried out from the inion down to the lowest cervical level of interest.

Cervical fixation can be performed before or after occipital fixation. Most constructs include at least two points of fixation on either side of the cervical spine. C1 can be an uppermost point of cervical fixation, but due to the increased technical demands of fixation at this level and the decreased space for the required rod bend in this area, it is not uncommon to leave C1 out of the occipitocervical instrumentation construct.

The plate position is then selected. This is generally midline and just below the inion. Again, a bur can be used to flatten the bottom flare of the external occipital protuberance to accommodate the plate (▶ Fig. 5.1). Screw paths are then drilled (▶ Fig. 5.2) and the screws placed. Although unicortical screws can be used, bicortical occipital fixation provides the strongest fixation. To do this, both the inner and outer table must be drilled and tapped prior to screw placement.

The occipitocervical rod will then be placed. This can be a single-piece contoured rod or a hinged/locking rod. Hinged rods may ease the process of rod preparation, but at the cost of increased hardware bulk and prominence (▶ Fig. 5.5). If the rods or plate extend above the superior nuchal line, a reverse bend of this portion should be considered to ensure that it will lie flat on the occiput. When rods are used, the point of maximum bend should be at the occipitocervical junction (▶ Fig. 5.6).

With wire placement, a suboccipital craniectomy is generally performed. Once the final rod position is determined, bur holes are drilled around the craniectomy, dura is dissected away from the inner table, and the bent wire tips are passed (▶ Fig. 5.4).

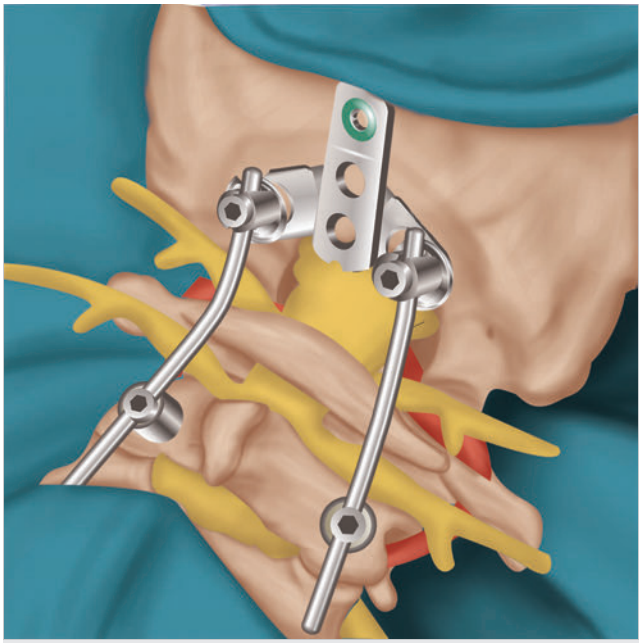

Fig. 5.6 Dual contoured rods connected to occipital and cervical instrumentation. Note the pivot point of the rod is at the level of the occipitocervical junction.

5.11 Bailout, Rescue, and Salvage Procedures

Occipital fixation with midline screws has become the primary method of occipital fixation. If there is poor purchase of midline screws, lateral supplemental fixation may be considered (▶ Fig. 5.3). If screws cannot be placed below the superior nuchal line, they may be placed cephalad to it with caution. Bear in mind that the transverse sinus typically runs deep to this landmark.

Pitfalls

- Perpendicular screw placement can be difficult due to the steep angle required close to the foramen magnum. To accommodate screw placement and maximize available bone thickness for screw purchase, it is recommended to keep the plate high enough on the occiput to optimize fixation while keeping the instrumentation below the superior nuchal line. This also ensures sufficient bony space below the plate for decortication and bone grafting.
- The appropriate occipitocervical alignment to lock in for fusion can be difficult to assess. The recommendations detailed previously with regard to erring on the side of flexion may be helpful to keep in mind.
- Lastly, poor fit or overly superior placement of the plate(s) may lead to hardware prominence that might cause pressure ulcers of the overlying skin with subsequent hardware exposure and infection.

6 Grafting Methods: Posterior Occipitocervical Junction and Atlantoaxial Segment

Robert K. Eastlack, Bradford L. Currier, and Alexander R. Vaccaro

6.1 Description

Several grafting techniques may be used to facilitate arthrodesis of the occipitocervical or atlantoaxial segments.

6.2 Key Principles

- Prepare the donor sites or bony bed adequately.
- Autograft bone is the gold standard choice in graft material.
- Adequate internal and/or external fixation plays an important role in maximizing fusion success.

6.3 Expectations

Thorough preparation of the grafting site and use of autograft bone with adequate stabilization should result in a healthy fusion mass.

6.4 Indications

- Occipitocervical instability
- Atlantoaxial instability
- Failed C1–C2 arthrodesis
- Painful degeneration of the occipitocervical-atlantoaxial junctions
- Congenital anomalies
- Tumor
- Ankylosing spondylitis

6.5 Contraindications

Grossly infected sites should be debrided and treated with appropriate surgical/medical management before application of internal fixation and bone grafting in some cases. Onlay bone grafting utilizing external immobilization alone has demonstrated acceptable fusion rates should internal fixation be concerning or not possible. The timing of the graft placement and instrumentation must be addressed on an individual basis. Shortened life expectancy (< 3–6 months) may obviate the usefulness of bone grafting, but in the setting of uncertainty it is prudent to err on the side of overtreatment.

6.6 Special Considerations

- Occipitocervical fusions require careful intraoperative positioning to leave patients in an optimized functional alignment.
- Preserve the subaxial muscular and ligamentous attachments to the spinous process of C2 (semispinalis cervicis muscles, interspinalis muscles, interspinous ligament) when not planning for extension to a subaxial cervical fusion.

6.7 Special Instructions, Positioning, and Anesthesia

- Be sure that the anesthesiologist is aware of the need for neuromonitoring as the choice of anesthetic may change when motor evoked potentials are utilized.
- Position the patient prone with the head held with cranial tongs or halo secured to the operating table with a Mayfield attachment.
- Position the occipitocervical junction intraoperatively using fluoroscopy. The intersection of lines drawn parallel with the opening of the foramen magnum and the superior end plate of C3 should approximate 45 degrees. Confirm that neutral cervical rotation has been obtained before fusing the atlantoaxial junction as well.

6.8 Tips, Pearls, and Lessons Learned

Autograft bone may be harvested from the posterior-superior iliac spine or ribs. Bicortical grafts should be obtained when the graft is providing structural support in the area of fusion. If there is inadequate structural or morselized autograft bone specimen available, allograft bone may be used or autograft bone can be supplemented with demineralized bone matrix adjuncts. Tricortical allograft iliac crest bone has been utilized with nearly equivalent fusion rates to autograft in posterior atlantoaxial fusion applications. Do not place bone graft directly on the neural elements, including the C2 exiting nerve root or ganglion.

Decorticate the occipital region of the skull below the external occipital protuberance to expose bleeding cancellous bone. This can be done with a high-speed bur following placement of occipital hardware. Analyze the preoperative computed tomography (CT) images for dimensions of bone in the area of expected fixation placement, as well as the location of neurovascular structures, such as intracranial sinuses. There is considerable anatomical variability. The occiput is thickest in the region of the external occipital protuberance (EOP), but the adjacent venous sinuses must be avoided. A thick midline keel of bone runs from the EOP to the foramen magnum and may be used for the optimum points of screw fixation. Do not stray greater than 2 cm laterally from the midline, as the bone thickness diminishes considerably.

Prepare the atlas and axis similarly prior to graft placement. It is very important to adequately expose and decorticate the C1 arch and laminae of C2. Using a Kerrison rongeur to decorticate the caudal portion of C1 and cranial portion of C2 will avoid a dural tear from the bur.

6.9 Difficulties Encountered

The absence of the C1 posterior arch or the need for a laminectomy at C1 or C2 may necessitate placement of bone graft into the atlantoaxial joints. Carefully elevate the C2 ganglion to expose the atlantoaxial joint on each side. Remove the cartilage within the joints with a curette or bur and pack morselized cancellous bone graft into the joints. Corticocancellous strut grafts can be applied laterally and held in place with wires or cables secured to the bone or the instrumentation. This bone graft can be carried up to a prepared occipital bony surface when occipitocervical fusion is desired. The occipital bone should be prepared sufficiently laterally from midline to accommodate the graft placement over the C1–C2 articulations.

6.10 Key Procedural Steps

6.10.1 Occipitocervical Grafting

This step can be accomplished in a variety of ways, depending on the extent of fusion required below the axis, as well as the accompanying instrumentation. Corticocancellous strips placed parasagittally in a longitudinal fashion can be employed (▶ Fig. 6.1). Alternatively, a large unicortical piece of iliac crest autograft can be placed over the occiput–C2 region, using a midline caudal notch to help with its positioning on the cephalad aspect of the C2 spinous process (▶ Fig. 6.2). There are additional options for autograft harvesting, including corticocancellous partial thickness resection of the calvarium above the planned construct. Rib excision/harvest has also been used with successful fusion, but requires a separate surgical site. Prepare the dorsal aspect of the posterior elements and occiput by decorticating them, and ensure that the cancellous surface of the graft abuts those areas well. The graft can be secured to the occiput by a midline screw or wire, or held in place by the overlying soft tissues. With newer rod/screw fixation techniques, morselized cancellous autograft bone appears to be sufficient if applied liberally to well-decorticated surfaces. Bilateral instrumentation in combination with secure occipital fixation obviates the apparent need for structural bone graft material. Because of the small surface area comprising the posterior arch of C1, we typically use a supplemental interlaminar bicortical bone graft (via one of the methods described below) over the posterior atlantoaxial interval.

6.10.2 Atlantoaxial Grafting

Brooks Technique

Two individual bicortical corticocancellous grafts (iliac crest or rib) are fashioned to fit snugly between the C1 and C2 laminae. The cephalad and caudal edges can be shaped concavely to accept the convex laminar edges they approximate (▶ Fig. 6.3). Once sublaminar wires are passed below both C1 and C2, the bony surfaces of the host bone are decorticated with careful attention given to preparing the caudal and cephalad aspects of the C1 and C2 laminae, respectively. This can be accomplished with a Kerrison rongeur or a high-speed bur. Gently use a midline laminar spreader to obtain mild distraction of the atlantoaxial interlaminar space, and place the grafts between the lamina parasagittally.

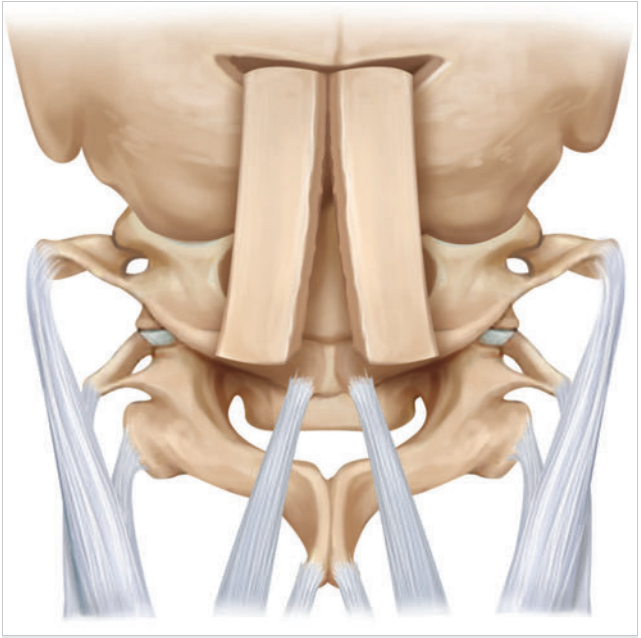

Fig. 6.1 Posterior perspective of the occipitocervical spine bony elements. Note the corticocancellous strips laid longitudinally on either side of the spinous processes parasagittally. The cancellous surface should be facing the decorticated surfaces of the occiput and laminae.

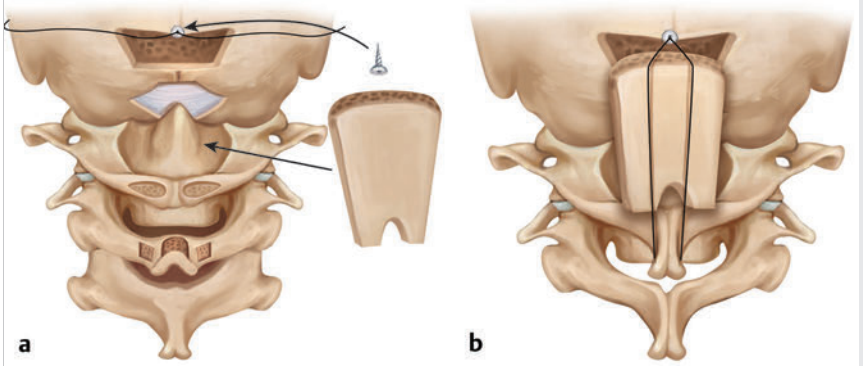

Fig. 6.2 **(a)** A large unicortical piece of iliac crest bone is applied to the occipitocervical junction, using a notch in the caudal edge that engages the cephalad margin of the C2 spinous process. (**b**) The inset of this unicortical iliac crest graft demonstrates the cancellous surface that should be placed in contact with the decorticated surfaces of the occiput and laminae.

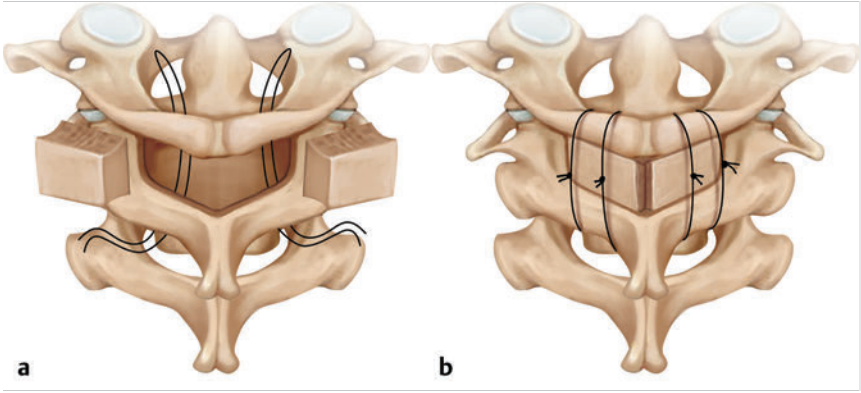

Fig. 6.3 Brooks technique for C1–C2 posterior arthrodesis. **(a)** Note the concave preparation of the cancellous mantle that mates with the lamina at both C1 and C2, and provides an extra measure of graft stability. Two pieces of bicortical iliac crest graft are placed between the C1 and C2 lamina on each side of the (**b**) C2 spinous process, and they are typically wired in place.

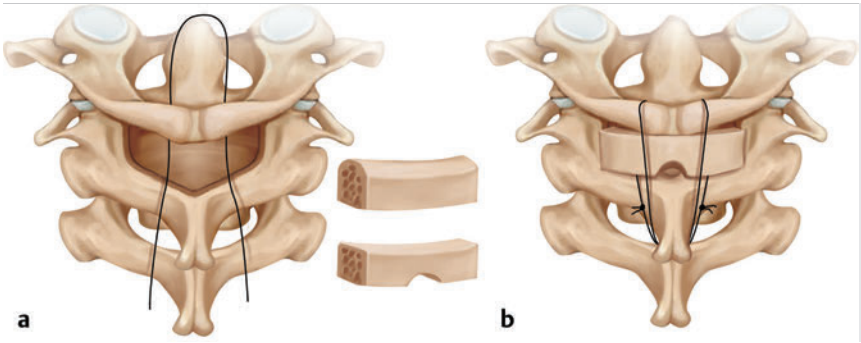

Fig. 6.4 **(a)** Dickman-Sonntag hybrid graft for C1–C2 posterior arthrodesis. This 4-cm piece of tricortical graft is excised from the iliac crest, and converted to bicortical via resection of the longitudinal section delineated by the dashed line. The curvilinear dashed line demonstrates the area of notch preparation that will engage the C2 spinous process. (**b**) After application of the hybrid graft between C1 and C2, wiring is typically employed to capture and stabilize the graft between the laminae.

Dickman-Sonntag Hybrid Technique

A 4-cm tricortical corticocancellous graft from the iliac crest or rib is converted to a bicortical graft with a saw. Harvest the graft from the posterolateral aspect of the crest starting approximately 2 cm lateral to the posterior-superior iliac spine to obtain a graft of ideal proportions. Trim the graft to match the length between medial edges of the right and left atlantoaxial articulations (▶ Fig. 6.4). The long edges can be contoured to key into the convex surfaces of the cephalad and caudal laminae. Sublaminar wires are placed only under C1, and bone graft sites are decorticated as in the Brooks technique, prior to placement of the graft. The graft is placed horizontally between the C1 and C2 laminae, with the concave surface of the graft placed toward the dura. A midline notch in the caudal surface of the graft typically aids in positioning of the graft, so that it conforms to the cranial surface of the C2 spinous process. The notch should be deeper anteriorly than posteriorly to match the upward or caudal slope of the C2 spinous process.

6.11 Bailout, Rescue, and Salvage Procedures

When inadequate laminar bone stock remains due to congenital anomaly or laminectomy, central placement of the bone graft must be accomplished with extreme caution. If the bone graft does not have secure fixation to the occipital and axial surfaces, the corticocancellous graft should be morselized and placed lateral to the spinal cord.

If the posterior arch of C1 fractures during atlantoaxial graft placement or fixation, grafting should be applied laterally as well. Utilizing morselized cancellous iliac crest autograft has been effective when placed between the posterior atlantoaxial bony surfaces and in combination with rigid internal fixation via bilateral transarticular screws. Care is taken to prevent the grafting material from falling between the lamina and contacting the spinal cord. A small amount of cancellous graft can be packed into the atlantoaxial joints, or corticocancellous strips may be placed dorsally to span the atlantoaxial articular recess. Avoid impingement with or placement of graft directly on the C2 nerve or the spinal cord. Immobilize the region postoperatively with a cervical orthosis or halo vest depending on the degree of instability, type of internal fixation, and the quality of the bone.

Pitfalls

- The course of the vertebral artery varies as it passes from lateral to medial just posterior to the lateral mass of C1. Limit exposure of the posterior arch beyond 8 mm from the midline to prevent injury to the vertebral artery in this area.
- When only atlantoaxial arthrodesis is desired, be careful to limit exposure of the occipital bone, particularly in children. Younger patients have a heightened propensity to autofuse the occipitocervical junction following exposure alone.

7 Posterior C1, C2 Fixation Options

James Lawrence

7.1 Description

A number of fixation options for posterior C1–C2 fusion using sublaminar wiring, lateral mass and pedicle fixation, transarticular fixation, or translaminar fixation are available.

7.2 Key Principles

Various fixation options exist for posterior fusion of C1–C2 depending on the pathology involved, the need for decompression, the integrity of the posterior elements, and the vertebral artery anatomy.

7.3 Expectations

In cases with intact posterior elements or abnormality of the vertebral anatomy course, sublaminar wiring of C1–C2 or translaminar C2 fixation in combination with C1 lateral mass fixation provide reduction of C1–C2 instability and osseous fusion while minimizing risk to the vascular anatomy. The techniques of transarticular fixation of C1–C2 or C1 lateral mass fixation with C2 pedicle screws provide three-column fixation, increased rigidity, and do not require the presence of intact posterior elements.

7.4 Indications

C1–C2 instability (odontoid fractures or pseudarthrosis, ligamentous instability from trauma or congenital/developmental conditions, os odontoideum, conditions requiring C1–C2 laminectomy)

7.5 Contraindications

- Previous/known vertebral artery occlusion
- Erosion of the C1 lateral mass (rheumatoid)
- Congenital occipitocervical fusion
- Anterior cord compression from infection, tumor, or pannus requiring an anterior approach

7.6 Special Considerations

Detailed preoperative assessment of osseous, neurologic, and vascular anatomy is critical to success. Computed tomography (CT) with magnetic resonance imaging (MRI) evaluation allows complete understanding of the fracture morphology, the integrity and anatomy of the atlantoaxial complex and the lateral mass/facet joint/pedicles, and the location of the vertebral arteries. Image guidance with intraoperative fluoroscopy or CT-guided navigation also provides significant information regarding fracture reduction, C1–C2 alignment, and screw trajectory.

7.7 Special Instructions, Positioning, and Anesthesia

- Consideration of awake intubation in the highly unstable patient
- Prone with a Mayfield pin holder/headrest
- Somatosensory (SSEP) and motor evoked (MEP) potentials / electrophysiologic monitoring
- Anteroposterior (AP) and lateral fluoroscopy or CT-guided navigation

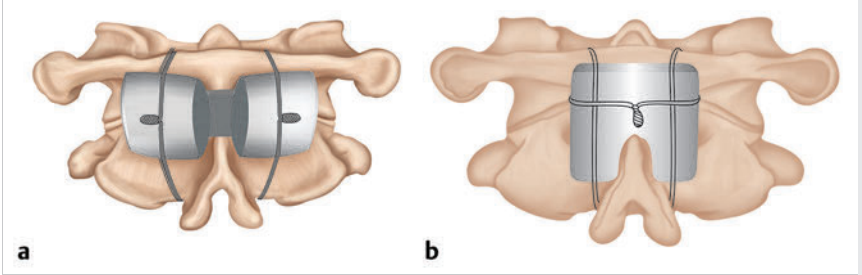

Fig. 7.1 **(a)** Wiring using Brooks' technique with paired corticocancellous grafts. (**b**) Wiring using Gallie technique with a single graft and inclusion of the C2 spinous process.

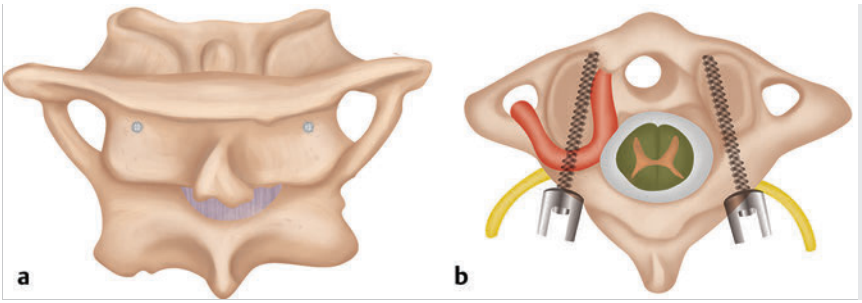

Fig. 7.2 **(a)** Starting point for placement of C1 lateral mass screws. (**b**) Axial view of C1 lateral mass screws.

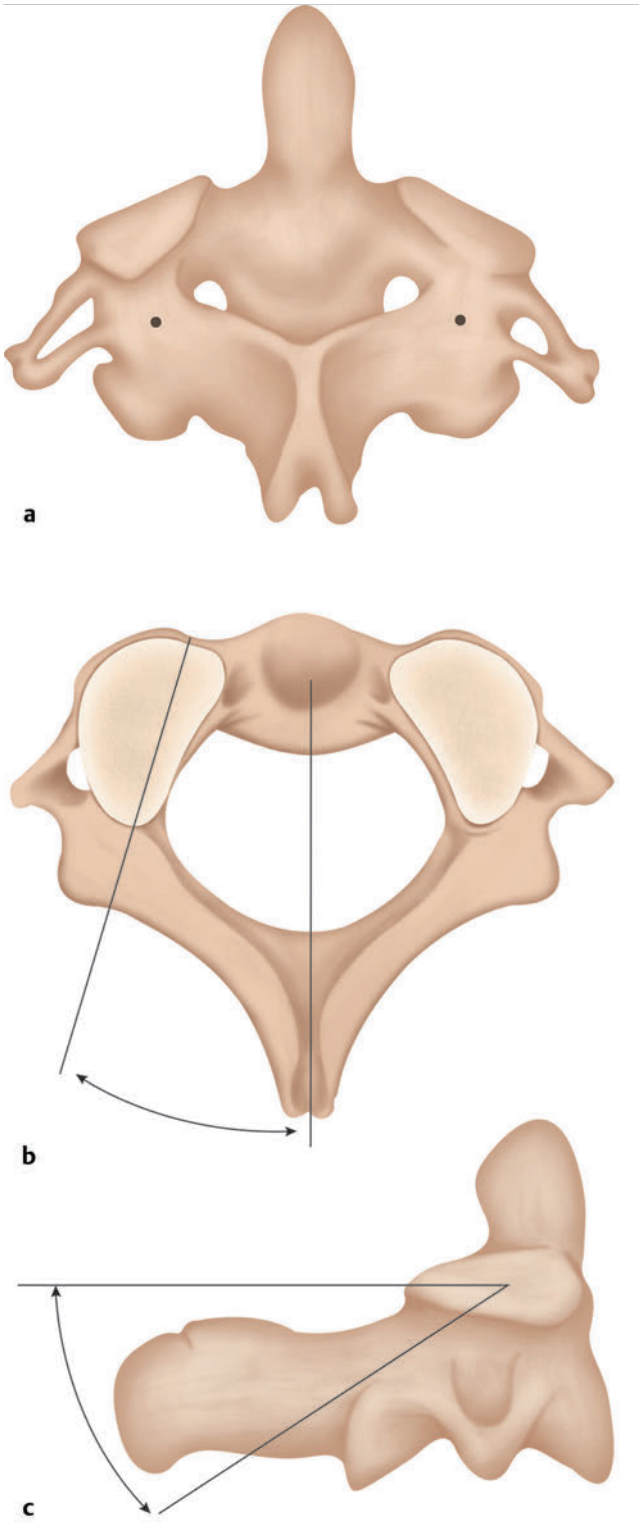

Fig. 7.3 **(a)** Palpation of the isthmus of C2 and starting point for C2 pedicle screw placement. (**b**) Medial angulation of the C2 pedicle screw. (**c**) Sagittal angulation of the C2 pedicle screw.

7.8 Tips, Pearls, and Lessons Learned

7.8.1 Sublaminar Wiring

Placement of the head in slight flexion can assist with wire passage. Removal of the ligaments on the cephalad and caudal aspects of C1 and the superior edge of C2 allows better visualization and easier wire passage. Notching of the laminae should be avoided. Passage of a suture (0 or no. 1) with a large curved needle followed by passage of the looped wire minimizes cord compression. Paired bone grafts (Brooks) or solitary bone graft (Gallie) with unicortical surface should be placed over decorticated posterior surfaces of C1 and C2.

7.8.2 Translaminar Fixation

Placement of the initial translaminar screw near the rostral margin of the C2 lamina at the junction of the spinous process and the lamina ensures adequate space for the contralateral screw on the caudal edge of the C2 lamina.

7.8.3 Transarticular Screw Placement and C2 Pedicle Screw Placement

Combination of image guidance and direct palpation of the bony landmarks assist in safe screw placement. A Penfield retractor or a nerve hook is used to directly palpate the C2 isthmus to guide the appropriate screw trajectory.

7.9 Difficulties Encountered

During sublaminar wiring, changes in SSEP/transcranial MEP should be treated with wire removal, decompression, and alternative fixation techniques. Inadequate laminar space for the accommodation of crossing screws or inappropriate trajectory can lead to failure of screw passage or intraoperative fracture in translaminar screw fixation. Obesity or significant cervicothoracic kyphosis can complicate transarticular screw placement, but preoperative positioning with fluoroscopy can be useful. The venous plexus posterior to the C1–C2 facet requires careful handling with bipolar electrocautery and packing with hemostatic agents. Pedicle breach during passage of C2 pedicle screws or anomalous position of the vertebral artery requires placement of a C2 pars screw or alternative fixation.

7.10 Key Procedural Steps

For translaminar wiring, exposure of the posterior aspect of C1 should be limited to 1.5 to 2 cm lateral to the midline to avoid vertebral artery injury. The ligaments on the rostral and caudal aspects of C1 and the rostral end of C2 should be removed. The C2–C3 ligaments should be maintained. A large curved needle with a looped suture is passed under C1 and C2 with care not to impinge the cord. One suture is used for a Gallie-type construct, two for a Brooks fusion. After wire passage, either the single wire is passed under C1 and wrapped around the spinous process (Gallie) or paired wires are passed under the C1/C2 laminae

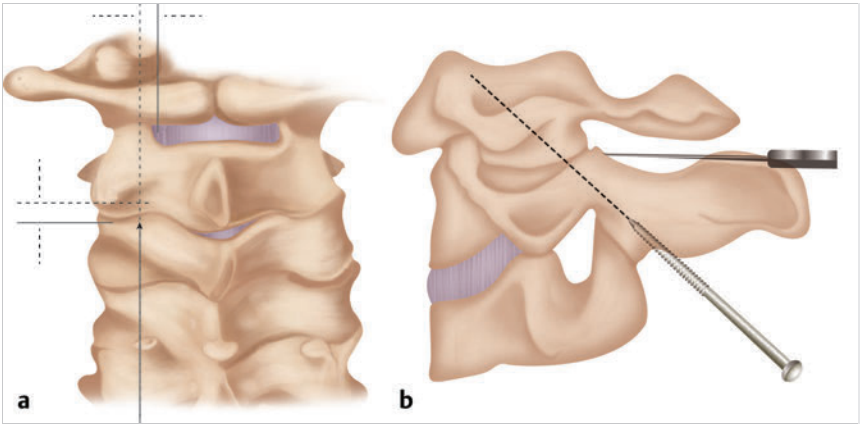

Fig. 7.4 **(a)** Starting point for C1–C2 transarticular screw placement. (**b**) Screw trajectory through the C1–C2 facet joint.

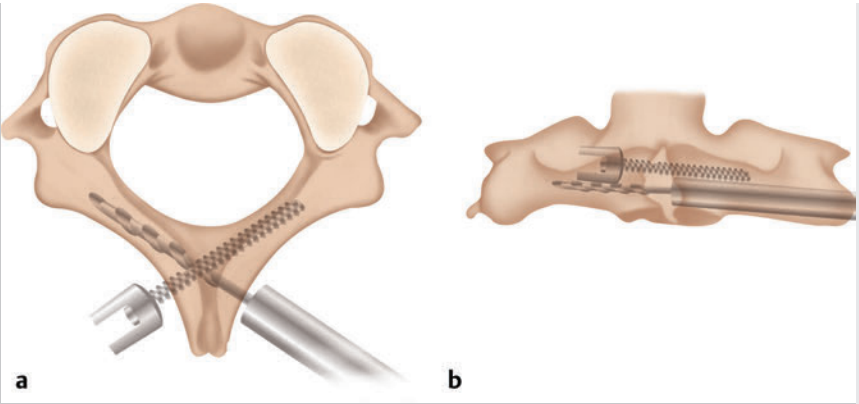

Fig. 7.5 **(a, b)** C2 translaminar screws.

(Brooks). In a Brooks fusion, paired unicortical autografts are placed dorsal to the C1/C2 laminae and tightened (▶ Fig. 7.1a). In a Gallie fusion, a large unicortical autograft is contoured and placed over the decorticated posterior laminae of C1/C2 and tightened with the looped wire (▶ Fig. 7.1b).

C1 lateral mass screws can be placed under direct visualization into the C1 lateral mass. A bur is used to make a starting point, followed by a drill under fluoroscopic control. The drill path is then tapped, and a unicortical or bicortical screw is placed. Care should be taken to medialize the screw adequately 15 degrees to avoid the internal carotid artery if a bicortical screw is placed (▶ Fig. 7.2).

The critical element for the placement of both transarticular screws and C2 pedicle screws is the identification and palpation of the isthmus with a nerve hook or a Penfield. This provides understanding of the degree of medial angulation necessary to avoid inadvertent misplacement and corresponding neural or vascular injury. The starting point for C2 pedicle screws is the superior and medial lateral mass (▶ Fig. 7.3a). A bur is used for the starting hole, followed by a straight pedicle probe, ball-tipped feeler, tap, and screw. The angulation is 15 medial and 20 cephalad, and typical screw length is 30 to 35 mm (▶ Fig. 7.3b, c). Transarticular screw placement requires both a more distal starting point and a more cranial angulation. The starting point should be made some 2 to 3 mm cephalad to the C2/3 facet joint, and the angle should be 15 degrees medial and approximately the sagittal angle determined under fluoroscopy (▶ Fig. 7.4). For either technique, exposure of the C1–C2 facet joint should be performed carefully with caudal retraction of the exiting C2 nerve, followed by curettage and bone grafting.

C2 translaminar screws are placed using starting holes on opposite sides of the lamina/spinous process junction, one cranial and one caudal. A bur is used for the starting hole, followed by a hand drill between the inner and outer tables. The initial screw must be carefully placed so as not to obstruct passage of the other (▶ Fig. 7.5). Preoperative planning is key to gauge the available space and screw lengths.

7.11 Bailout, Rescue, and Salvage Procedures

C1/C2 transarticular or polyaxial (C1 lateral mass and C2 pedicle screws) can be used if sublaminar wires cannot be passed or translaminar fixation fails. Vertebral artery injury should be treated with immediate hemostatic agents, tamponade, and urgent neurovascular consultation for either further arterial exposure and ligation or endovascular treatment. Unilateral fixation can be employed in the setting of pedicle breach or if one side is unsuitable for either transarticular placement or C2 pedicular fixation. Extension of instrumentation and fusion to either the occiput or distally can be performed if fixation is inadequate at C1–C2. A halo device can be employed if internal fixation is not feasible.

Pitfalls

- Posterior sublaminar wiring should be performed with small wires to avoid spinal cord injury. As a less rigid construct than the alternatives, if inadequate fixation is achieved, supplementary halo fixation may be required.
- Inadvertent inferior or lateral placement of transarticular screws can lead to injury of the vertebral artery, while medial placement poses a risk of spinal cord injury.
- Small pedicle size, breach of the pedicle, vertebral artery injury, and spinal cord injury are all pitfalls of C2 pedicular fixation.
- Bicortical C1 lateral mass screws and excessively long C1–C2 transarticular screws risk injury to the internal carotid artery unless adequate medial angulation is maintained.

8 Reduction Techniques for Atlantoaxial Rotary Subluxation

Justin W. Miller and Rick C. Sasso

8.1 Description

Atlantoaxial rotatory subluxation occurs when there is a displacement of C1 on C2. There are varying degrees of subluxation, with four subtypes previously described by Fielding et al. The most common is type I, which involves rotation of the atlas on the axis without anterior displacement of the atlas. The pivot point is the atlantodens articulation with an intact transverse atlantal ligament (TAL). The other subtypes, which are less common, involve displacement of the atlas in the anterior (types II and III) or posterior (type IV) direction. The TAL and/or dens are felt to be attenuated or incompetent in types II to IV. Rheumatoid involvement and trauma are common etiologies for TAL incompetence.

Atlantoaxial rotatory subluxation is most commonly seen in children and usually associated with torticollis (▶ Fig. 8.1). Though the true etiology is not known, there are many theories, all of which include an initial injury/inflammatory process of the atlantoaxial joint complex with or without associated muscular spasm. Over time, the deformity can become fixed, resulting in pain and possible neurologic compromise. Common inciting factors are felt to include trauma or infection of the upper respiratory tract (Grisel's syndrome).

The majority of atlantoaxial rotatory subluxations in children resolve spontaneously with minimal intervention. The deformity may initially be treated with a short course of anti-inflammatory medication and a rigid cervical collar. If the subluxation does not improve within 1 week, the patient should be admitted to the hospital and placed in cervical traction. If these maneuvers do not reduce the deformity, then open reduction and internal fixation is contemplated. The simplest approach to the atlantoaxial complex for reduction and instrumentation with fusion is posterior. The most powerful reduction forces can be applied to the atlas and axis via direct screw instrumentation, which also provides rigid stabilization to optimize fusion potential.

Fig. 8.1 A 10-year-old girl 5 months after a car crash with a fixed torticollis. This severe deformity continued despite multiple attempts of closed reduction and immobilization including a halo.

8.2 Key Principles

- Fixed atlantoaxial rotatory subluxation is best approached posteriorly.
- Direct visualization allows for safe reduction and stabilization.
- Full exposure and knowledge of landmarks prevent iatrogenic complications.
- Rigid C1–C2 fixation can aid with and maintains reduction.
- Resolution of deformity/pain is expected following treatment.

8.3 Expectations

Anatomical reduction of the atlantoaxial articulation with subsequent resolution of the torticollis deformity is expected (▶ Fig. 8.2). With direct access to the facet joints and manipulation through segmental fixation in C1 and C2, perfect reduction is sought.

8.4 Indications

The indications for this technique of direct reduction and internal fixation with polyaxial screws in C1 and C2 connected

Fig. 8.2 The same girl as in ▶ Fig. 8.1 one day following open reduction and internal fixation of the C1–C2 joints.

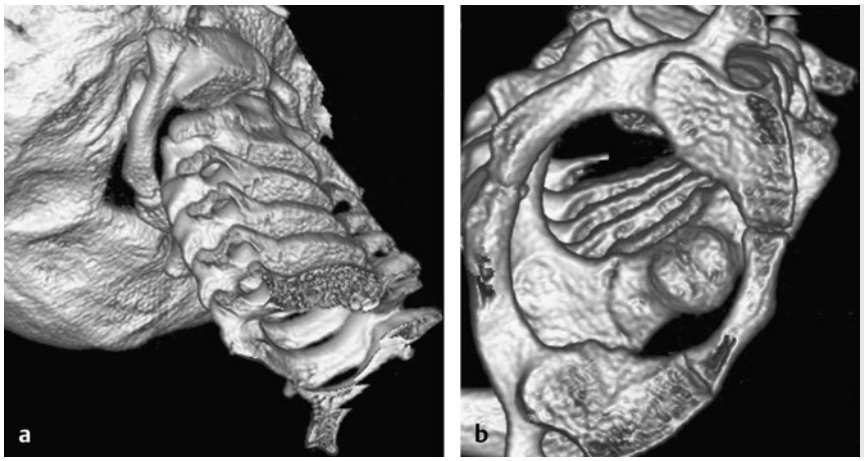

Fig. 8.3 Representations of preoperative computed tomography (CT) scans with reformatted reconstructions. Right C1–C2 joint with the lateral mass of C1 anterior to the C2 superior articular surface; (**a**) inferior view and (**b**) superior view.

through rods are irreducible rotatory subluxations of C1–C2 that are unresponsive to nonoperative treatment (▶ Fig. 8.3)

8.5 Contraindications

The contraindications are those subluxations/dislocations that reduce and are stable with nonoperative methods.

8.6 Special Considerations

Visualization and complete mobilization of the atlantoaxial complex requires full access to the posterior aspect of C1 and C2, including the facet joints, which are obscured by the C2 nerve root. Thus, the C2 nerve root must be circumferentially mobilized. It is of utmost importance to also understand the course of the vertebral artery (VA) as it travels from C2 to the occiput.

8.7 Special Instructions, Positioning, and Anesthesia

Patients are positioned in the prone position on a standard OSI Jackson table with horseshoe attachment supporting the head and neck. If the patient is too small, a standard operating table may be used with chest rolls. The patient's arms are secured at the side and shoulders, gently taped to allow proper visualization. All appropriate areas are padded with foam. The buttock is taped to prevent sliding of the patient as the bed is placed in reverse Trendelenburg position, limiting bleeding during exposure. Standard anesthetic techniques are used during this procedure.

8.8 Tips, Pearls, and Lessons Learned

An important tip for mobilizing the C2 nerve is control of the venous plexus, which surrounds the nerve as it courses posterior to the C1–C2 facet joint. It is necessary to gain complete control of this plexus so that the nerve can be retracted both cephalad and caudad to fully visualize the joint. If the C2 nerve is mobilized without first coagulating the venous plexus, significant blood loss and poor visualization will likely result in undue difficulty. A combination of bipolar cautery, thrombin-soaked Gelfoam (Pfizer Pharmaceuticals), and/or FloSeal hemostatic matrix (Baxter Healthcare) aids in coagulation of the venous plexus.

The VA is potentially placed at risk with traditional transarticular C1–C2 screws and C2 pedicle screws. An anomalous VA would preclude transarticular fixation, and has an incidence as high as 20% based on cadaveric research. Aberrant VA anatomy or pedicle size could also prevent the insertion of a C2 pedicle screw. To avoid the potential pitfalls and technical difficulties associated with transarticular or pedicle fixation, a much simpler and extremely safe alternative is C2 translaminar fixation. The C2 lamina is the largest in the cervical spine and readily accepts a 3.5-mm or 4.0-mm screw. The C2 laminae are fully exposed and the starting point for screw insertion is made with a high-speed bur at the cephalad junction of the spinous process and lamina on one side. A cervical awl is then used to prepare the trajectory down the contralateral lamina. A common error is to prepare the trajectory at too steep of an angle. The surgeon's hand must be flattened with regard to the horizontal with the drill aimed along the angle of the lamina that is clearly visible. It is better to breach the posterior cortex slightly, as opposed to the ventral cortex, which potentially places the neural elements in danger. A tap can be used to prepare the first several threads and a polyaxial screw is then inserted. The opposite screw is placed in the same fashion with the starting point at the caudal aspect of the lamina. There is limited "real estate" for placement of both screws; hence, planning is needed for each starting point to allow proper insertion. Average screw lengths are between 25 and 30 mm depending on the anatomy.

Although it may be tempting to begin the C1 lateral mass screw in the posterior arch of C1, this should be resisted. This recommendation is based on the variable course of the VA (which runs in the groove along the cephalad aspect of the C1 posterior arch). The VA may dip caudally, with only a thin wafer of bone separating the VA from where a screw would insert. Insertion of the screw directly into the lateral mass, however, is an extremely safe technique. The spinal cord is not at risk as the starting point for the screw is at the anterior aspect of the spinal canal. The VA is not at risk because it is lateral and cephalad to this entry point. As stated previously, the challenge with

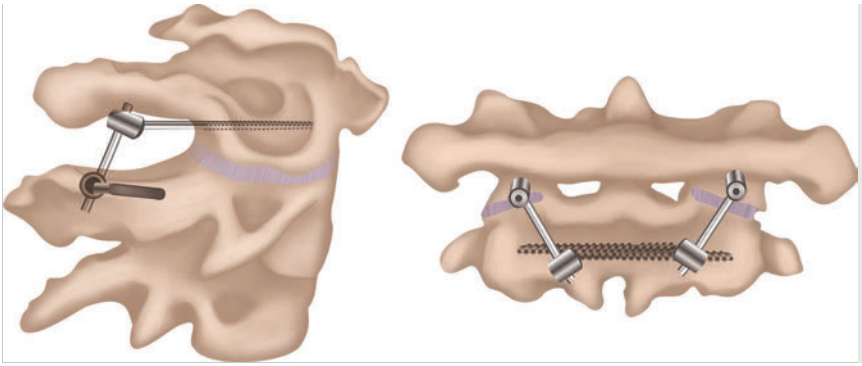

Fig. 8.4 Final construct with bilateral C1 lateral mass and C2 translaminar screws connected to rods in a reduced position.

adequate exposure of the lateral mass is the venous plexus surrounding the C2 nerve root. The key to easily placing the C1 lateral mass screw is fully visualizing the lateral mass. To accomplish this, the C2 nerve root and associated venous plexus must be mobilized and retracted caudally. A Penfield or freer elevator retractor can be placed in the C1–C2 facet joint, with the C2 nerve retracted below. This should allow perfect visualization of the lateral mass for screw insertion.

8.9 Difficulties Encountered

- Mobilization of the C2 nerve and control of the venous plexus
- Disimpaction of the C1–C2 joints and complete reduction can be challenging depending on chronicity of the deformity.
- Placement of instrumentation is critical and allows little margin for error; therefore, strict adherence to landmarks and insertion technique is needed.

8.10 Key Procedural Steps

- Posterior exposure of C1–C2 with mobilization of the C2 nerve roots
- Disimpaction of the C1–C2 joints and removal of the articular surfaces
- Insertion of the polyaxial screws into the lateral masses of C1 and the laminae of C2
- Anatomical reduction of the atlantoaxial joints by using the screws as "joysticks" as well as levering instruments between the articular surfaces (see **Video 8.1**)
- Seating of rods into the polyaxial screws to fix C1–C2 in an anatomical position (▶ Fig. 8.4)
- Application of bone graft into the decorticated atlantoaxial joints bilaterally

8.11 Bailout, Rescue, and Salvage Procedures

If laminar screws are unable to be placed, a C2 pedicle screw or transarticular screws could potentially be placed if anatomy allows. If a screw technique cannot be implemented for whatever reason, then posterior fusion with a cable or wire construct can be performed. A Brooks or modified posterior spinous process wiring technique may be utilized if the posterior elements of C1 and C2 are intact. Postoperatively, however, halo immobilization would be necessary because this form of fixation is profoundly weaker than the described polyaxial screw/rod construct.

Pitfalls

- If the rotatory subluxation is not acute, significant articular and periarticular scarring with adhesions may prove reduction challenging.
- There may also be a mechanical block to reduction as a result of the dislocated articular surfaces. Breaking up the adhesions within the joint and distraction of the articular surface help to overcome this challenge.

9 Posterior Cervical Wiring

Howard B. Levene, George M. Ghobrial, and Jack Jallo

9.1 Description

Posterior cervical wiring is a relatively simple and inexpensive technique for achieving cervical stability by providing a posterior tension band that resists flexion. Although this procedure has been largely replaced by screw-rod constructs, at one time this technique was the preferred procedure for posterior cervical stabilization. As posterior cervical wiring is less rigid than lateral mass and pedicular fixation, posterior cervical wiring results in lower rates of fusion than the more contemporary techniques of immobilization. Most surgeons use posterior cervical wiring on a limited basis, often in combination with forms of internal fixation. Therefore, the technique remains a valuable supplemental or salvage procedure. There are three general types of wiring: (1) spinous process wiring, (2) facet wiring, and (3) sublaminar wiring. Although sublaminar wiring continues to be useful for atlantoaxial fixation, it generally has been abandoned for subaxial cervical spine fixation due to the comparatively high risk of neurologic injury when compared with modern fixation systems.

Spinous process wiring and facet wiring share the fundamental ability to fuse adjacent levels through the creation of a posterior tension band. Wires are passed through a bony element (spinous process or facet) and either looped over or passed through another facet or spinous process. In some cases they are attached to a structural bone graft for further stability and a source of fusion material.

There are multiple techniques for simple interspinous wiring: Rogers wiring, Whitehill modification of Rogers wiring, the Benzel-Kesterson modification of Rogers wiring, Bohlman and McAfee triple-wire technique, and the Murphy-Southwick modification of the Rogers technique. Lastly, facet wiring methods include the Cahill oblique facet wiring and Callahan nonoblique facet wiring techniques; these have generally grown out of favor due to the elevated risk to the posterior neural elements and they provide no added benefits to the patient.

9.2 Key Principles

- Posterior wiring requires intact posterior elements: do not attempt in the setting of trauma in the presence of fractured lamina or disruption of the posterior elements.
- A careful review of preoperative imaging is vital to avoid devastating neurologic injury due to anomalous vertebral arteries, cervical fractures, or congenital anomalies such as nonbony union of the posterior cervical arch.
- An optimal wiring choice is left to the discretion of the surgeon on a case-by-case basis.

9.3 Expectations

The Rogers method and its various modifications are expected to provide cervical stability to a single subaxial cervical motion segment. To stabilize additional levels, the procedure can be repeated. The Murphy-Southwick modification of the Rogers technique is designed to stabilize additional segments.

9.4 Indications

Cervical wiring is indicated for subaxial instability resulting from trauma, neoplasm, degeneration, or infection. Cervical wiring allows for the creation of a posterior tension band to prevent progression of deformity, alleviate pain, and promote bony fusion.

9.5 Contraindications

These wiring techniques are contraindicated when there is an incomplete posterior bony ring, poor bone quality, or additional stability requirements (extension, rotation, lateral motion) beyond what can be delivered by posterior wiring.

9.6 Special Considerations

When choosing posterior wiring, it is important to remember that wiring provides almost no stability in extension, lateral bending, or axial rotation.

9.7 Special Instructions, Positioning, and Anesthesia

When positioning, the patient is placed prone with a neutral cervical spine or in slight extension. A Mayfield pin holder and cervical traction are options; however, a Mayfield pin holder is frequently used due to its ability in maintaining cervical alignment and avoiding any contact with the orbits.

9.8 Tips, Pearls, and Lessons Learned

Posterior wiring requires intact posterior elements. Avoid this technique in cases of severe instability. Failure to review preoperative imaging could result in catastrophic injury to anomalous vertebral arteries, or cervical fracture due to congenital anomalies such as nonbony union of the posterior cervical arches. Use this wiring as a stand-alone device only when the anterior and middle loadbearing columns are intact and a posterior tension band needs to be restored. A rigid cervical collar or halo may be required for stability during fusion. Facet wiring can be used when the lamina or spinous process of the adjacent rostral segments is missing. When using autograft, ribs make good posterior strut grafts versus iliac crest due to their natural curvature. Stainless steel, titanium, and polyethylene cables are available; 16- to 20-gauge metallic wires are the preferred sizes. Stainless steel wires have the best tensile strength. Titanium is more susceptible to fatigue notching than stainless steel, but it

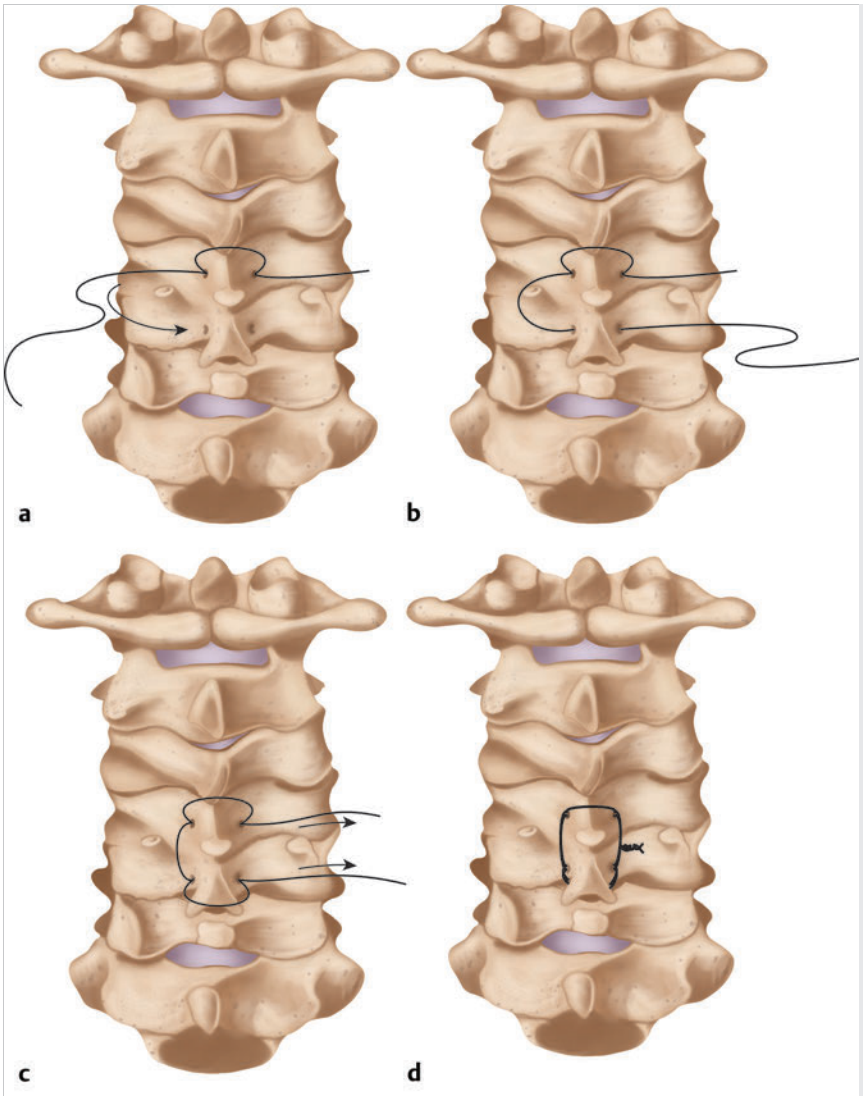

Fig. 9.1 Rogers interspinous wiring. This technique is used commonly for a single-level fusion. The perpendicular hole is drilled at the base of the spinous process of two adjacent levels. (**a**) Single cable loops through the superior level. (**b**) Cable end passes through the inferior level. **(c)** Cable then loops around inferior process. **(d)** Construct is tightened.

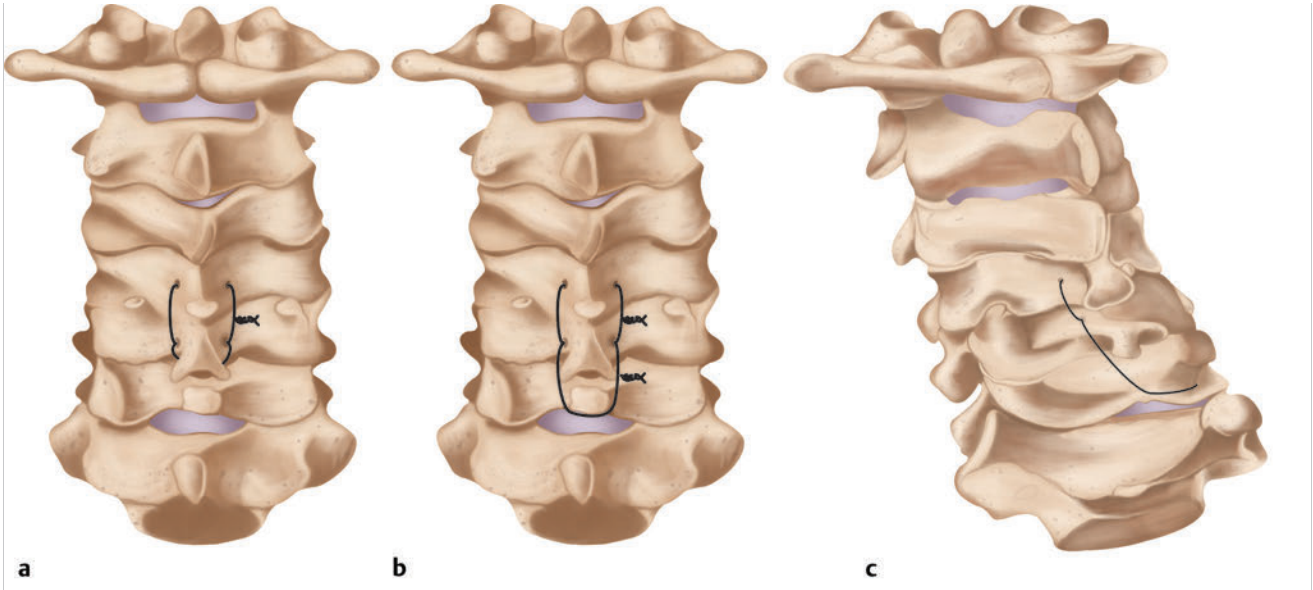

Fig. 9.2 Whitehill modification. (**a**) Single passage of cable through the superior spinous process base and loops under inferior spinous process. (**b**) Repeat for additional levels. (**c**) Repeat for additional level: lateral view.

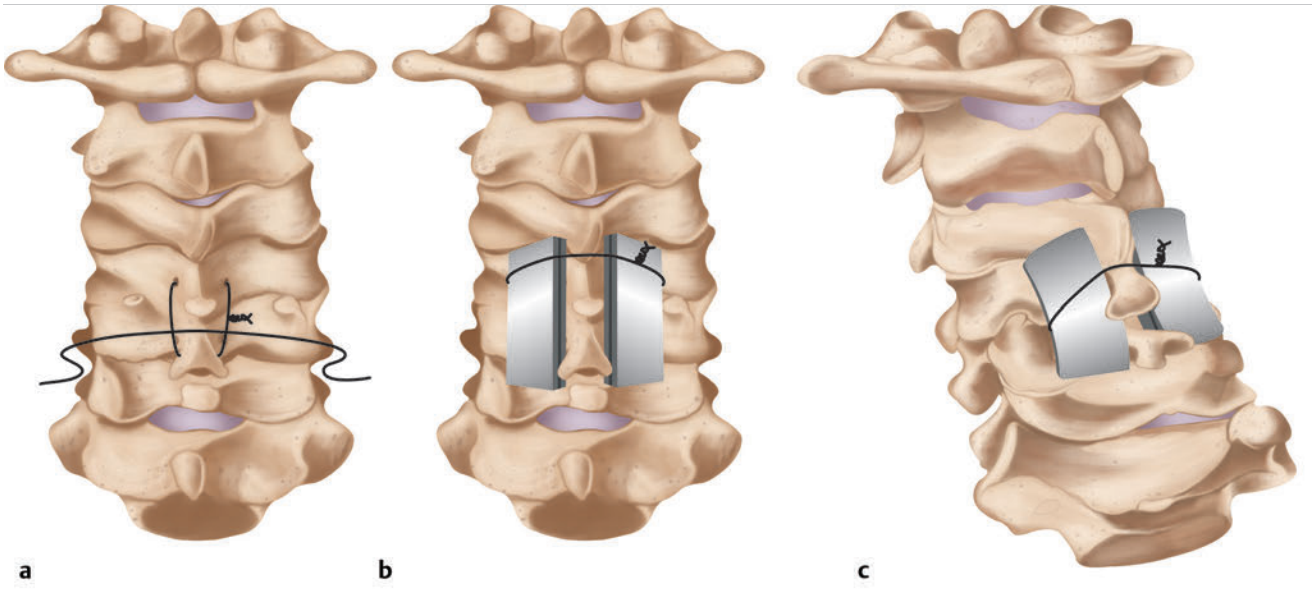

Fig. 9.3 Benzel-Kesterson modification. (**a**) Single passage of cable through superior spinous process as in the Whitehill modification. **(b)** Second cable passed deep to encircling cable. (**c**) Second cable affixes graft.

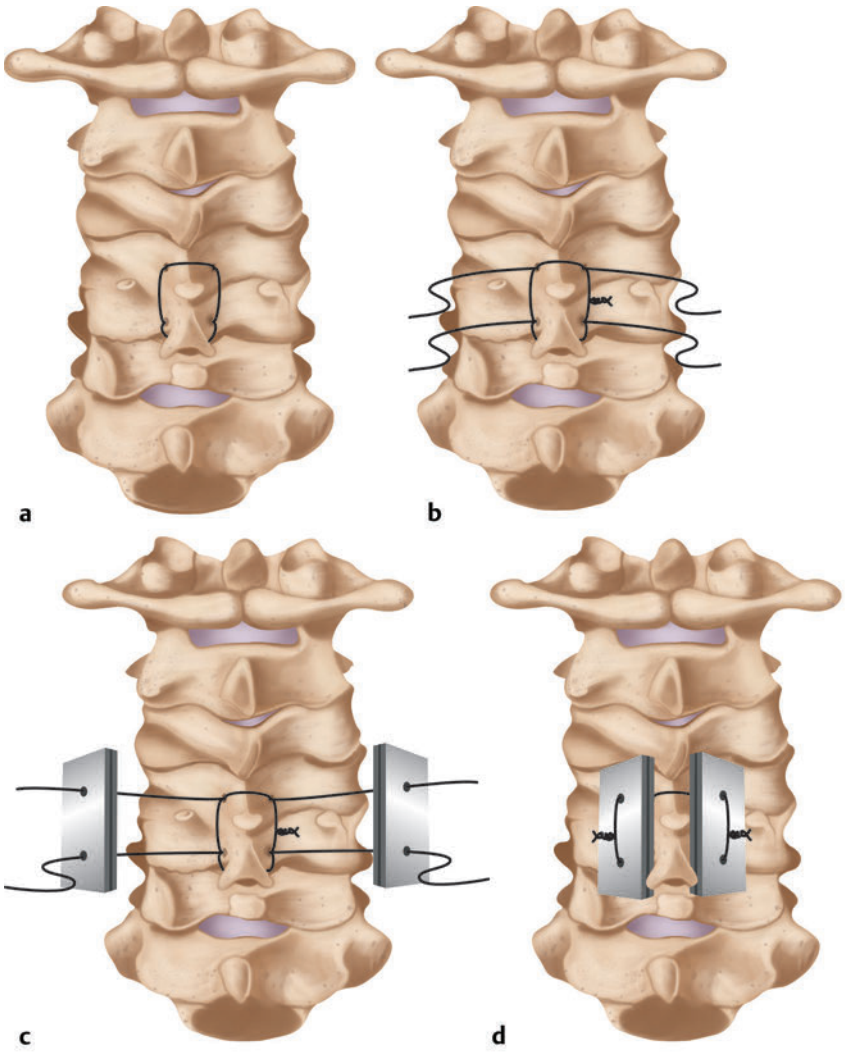

Fig. 9.4 Bohlman and McAfee triple-wire technique. (**a**) Begin as in the Rogers technique. (**b**) Additional cables are passed through the superior and inferior holes. **(c)** Additional cables are threaded through the graft. **(d)** Construct is tightened.

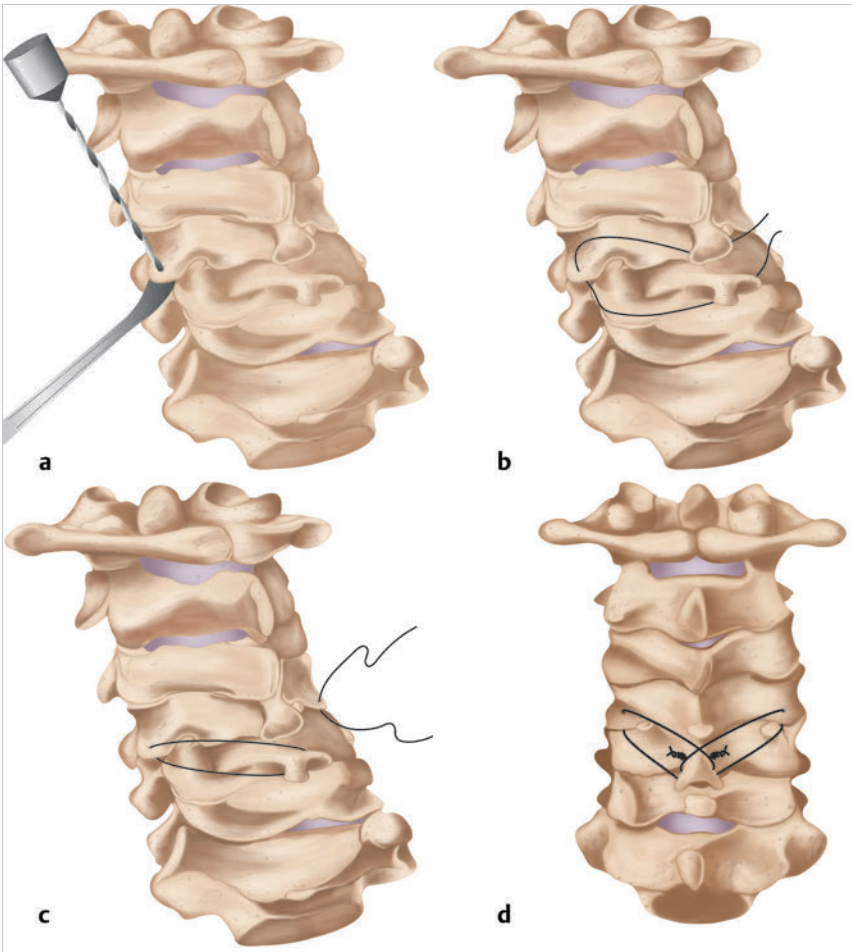

Fig. 9.5 Cahill oblique wiring. (**a**) Drill holes perpendicular to inferior facet of uppermost motion segment. (**b**) Pass cable through hole and loop over spinous process at inferior level. (**c**) Repeat contralaterally. **(d)** Construct is tightened.

has a better magnetic resonance imaging (MRI) profile. Polyethylene cables exhibit more creep than metal alloys, but have the best MRI profile. Braided (22-gauge) metallic cables possess a good combination of strength and handling properties. The choice of optimum wiring materials is left to the discretion of the surgeon on a case-by-case basis.

9.9 Difficulties Encountered

- Avoid overtensioning wires, a maneuver that will not increase stability, but instead may result in foraminal stenosis, a hyperextension deformity, or worse—wire breakage or pullout.
- In the case of severe disruption of the posterior elements, consider using a segmental screw-rod construct or if possible an anterior approach.

9.10 Key Procedural Steps

In all techniques, a midline incision is made. Using sharp, blunt, and electrocautery dissection, the incision is extended deep to the superficial fascia. The midline raphe is identified. Dissection is performed bilaterally down along the spinous processes. Lateral exposure identifies the medial aspect of the lateral masses.

Fluoroscopy or a lateral plain X-ray is used to identify the correct surgical level. Trauma to the facet capsule and ligaments is avoided. For the Rogers interspinous wiring technique, a right-angle dental drill is used to make a hole at the base of the spinous process dorsal to the spinal laminar junction at each respective level. The drill hole for the cephalad vertebrae is in the superior third of the spinous process, and the drill hole for the caudal level is in the inferior third of the spinous process. A wire is passed through the hole and looped above the spinous process for the cephalad vertebral level. The loop is passed inferior to the spinous process for the inferior vertebral level. The wire ends are now tightened together. Remember to decorticate the spinous processes and the laminae for bone grafting (▶ Fig. 9.1). In the Whitehill modification of the Rogers wiring technique, a hole is not drilled in the caudal vertebral spinous process. Instead, the wire is looped under the caudal spinous process prior to tightening (▶ Fig. 9.2). This process may be repeated at several levels. The Benzel-Kesterson modification of the Whitehill technique calls for an additional wire to be passed through the drill holes to be used to attach to structural grafting material laid bilaterally along the posterior elements (▶ Fig. 9.3). The Bohlman and McAfee triple-wire technique is similar to the Rogers technique at the superior and inferior vertebral levels. The first cable is passed through holes made within the spinous processes of the superior and inferior vertebral levels as with the Rogers technique. Two separate cables are

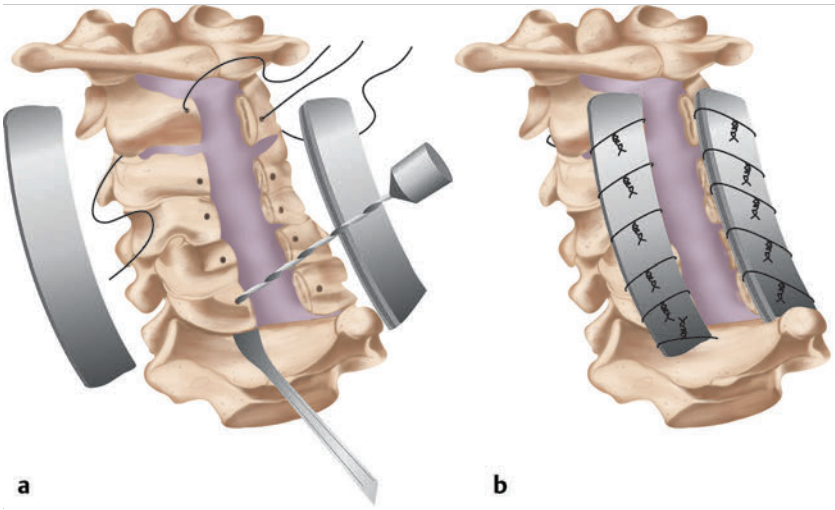

Fig. 9.6 Callahan facet wiring. (**a**) Drill holes perpendicular to inferior facet of each motion segment. Pass a cable through each hole in a cranial-caudal direction. One cable is used per hole. **(b)** Cables are tightened around a strut graft. Take care to spare the most caudal facet joint by using a cable through the spinous process rather than passing a cable through the facet joint.

then passed through these holes and are used to affix two strut grafts along the posterior elements on each side (▶ Fig. 9.4). The Murphy-Southwick modification of the Rogers technique allows for fusion of two adjacent motion segments. Holes are drilled into each respective spinous process as above, and wires are placed and tightened to incorporate all three spinous processes.

In facet wiring, the wires attach a facet to an adjacent facet or to an adjacent spinous process. By creating a tension band from the facet to the spinous process, rotational stability is augmented as in a reduced facet dislocation. Expose as above, except that the lateral masses/facets must be fully exposed. Remove the facet joint capsules and enter the facet with a small elevator and curette or drill away the articular cartilage. Drill a small hole perpendicular to the plane of the facet. Protect the nerve root and vertebral artery with a small dissector. For the Cahill oblique wiring, place the wire and loop through the spinous process below. Repeat contralaterally (▶ Fig. 9.5). For the Callahan wiring technique, the wires loop through a bony graft (rib or iliac crest) and do not connect with the spinous processes (▶ Fig. 9.6).

9.11 Bailout, Rescue, and Salvage Procedures

If a posterior element fracture is present, one can incorporate an additional level above or below the intended fusion levels. Alternatively, other fixation and fusion techniques may be utilized such as pedicle screws, lateral mass screws, or rarely laminar hooks or clamps.

Pitfalls

- Avoid overtensioning wires, which may result in a hyperextension deformity or iatrogenic foraminal stenosis. Overtensioning wires may also lead to wire breakage or pullout. (Use 8- to 12-inch-pound torque for normal adult bone.)
- Unilateral facet wiring in the setting of a bilateral facet subluxation may result in rotary instability and will not confer adequate stability.
- When fusing, do not disrupt the facet joints at cranial or caudal nonfused segments.
- Do not allow metals of different alloys to be in contact, as they will create an electric potential and promote corrosion.

10 Cervical Lateral Mass Screw Placement (C3–C7)

Daisuke Sakai, Yu-Po Lee, and Steven R. Garfin

10.1 Description

How to safely place screws within the cervical lateral mass while avoiding injury to the surrounding neurovascular structures is described.

10.2 Key Principles

Unicortical or bicortical screws may be placed safely within the lateral masses of the cervical spine (C3–C7).

10.3 Expectations

Lateral mass screws and rods provide rigid segmental fixation in cases of trauma, tumor, or to enhance fusions.

10.4 Indications

Cervical instability due to trauma, tumor, following a multilevel anterior diskectomy or corpectomy and strut grafting, or following posterior cervical laminectomy

10.5 Contraindications

- Aberrant vertebral artery anatomy
- Fracture of the lateral mass
- Absent or small lateral mass (C7)

10.6 Special Considerations

Detailed preoperative imaging using plain radiographs and magnetic resonance imaging (MRI) is necessary prior to surgery to adequately assess local anatomy, including the location of neural structures and the vertebral arteries. Computed tomography (CT) is helpful in certain cases for better assessment of the bony anatomy. A CT base navigation system may also be helpful.

10.7 Special Instructions, Positioning, and Anesthesia

If the procedure is to be performed in an unstable spine, awake intubation and positioning is recommended. Electrophysiologic monitoring is also helpful. Place the patient prone in the reverse Trendelenburg position with a Mayfield pin headrest or foam pillow. Use of a carbon Mayfield headrest is often helpful if using fluoroscopy. The neck may need to be slightly flexed in patients with a large occiput that is preventing access to the cervical vertebrae. Avoid forceful or excessive flexion. Tuck in the patient's arms at the sides. Use 3-inch tape to provide longitudinal traction to the shoulders. This aids in radiographic visualization of the lower cervical spine.

10.8 Tips, Pearls, and Lessons Learned

Taking an X-ray once the patient has been positioned is helpful for checking the alignment of the cervical spine and for planning the incision. This avoids having to reposition the patient after he or she has been prepped and draped or having to enlarge the incision or violating facet joints that were not intended to be fused. The most prominent spinous processes to palpation are C2, C7, and T1. Also, C6 is the last bifid spinous process, and the vertebral arteries do not usually run in the transverse foramen of C7. Care should be taken in the exposure to stay midline in the ligamentum nuchae. Straying laterally into muscle causes bleeding that will impede visualization of the lateral masses. Care should also be taken not to dissect the muscles off of the spinous process of C2, as this could lead to potential C2–C3 instability. The drill for the lateral mass screw is aimed 15 to 20 degrees cephalad and 30 degrees laterally relative to the vertebrae. Adjustments in the position of the neck and in the table may make it difficult to judge the orientation of the vertebra. Placing a Penfield no. 4 elevator (Integra Miltex) in the facet joint can be helpful in clarifying the orientation of the facet joint and thus the proper trajectory of the drill. Also, it is important to remember that the lateral mass of C7 is smaller and a steeper trajectory is often needed.

10.9 Difficulties Encountered

Should lack of stable fixation become a problem with a unicortical screw, bicortical fixation may improve screw purchase. Also, a salvage screw may improve screw fixation. The most inferior screw must not violate the facet joint as this may lead to pain at the adjacent level.

10.10 Key Procedural Steps

Make a midline incision at the desired level. Proceed through the ligamentum nuchae to the spinous processes. Use a subperiosteal dissection to expose the posterior elements and the lateral masses. Care should be taken not to violate the facet joints that are not to be fused (see **Video 10.1**). The starting point for the lateral mass screws should be in the middle of the lateral mass in the cephalad–caudad plane and 1 mm medial to midline in the medial lateral plane (▶ Fig. 10.1). Use a 2-mm pneumatic bur to penetrate the cortex. Use a 2.5-mm drill with a 14-mm stop to drill the hole. A 14-mm screw is usually sufficient for bicortical fixation. The drill should be aimed 15 to 20 degrees cephalad and 30 degrees laterally (▶ Fig. 10.2, ▶ Fig. 10.3). This should avoid injury to the vertebral artery, which generally lies in the midline of the lateral mass, and the nerve roots, which run inferiorly as they exit the neuroforamen. If the spinous process is too prominent and prevents positioning the surgeon from aiming the drill in the desired trajectory, partial resection of the spinous process may be performed so that the drill can be aimed in the proper trajectory. The hole

depth is measured and tapped; 3.5-mm polyaxial screws with favored angles are helpful for placement of the connector rods. If bicortical fixation is desired, start with a 10-mm drill and increase 2 mm in sequential fashion until the other cortex is breached.

10.11 Bailout, Rescue, and Salvage Procedures

Should the vertebral artery be violated during the procedure, hemostasis is achieved by packing the site with thrombin-soaked Gelfoam and bone wax. Instrumentation on the contralateral side should be avoided to ensure that at least one vertebral artery remains intact. In situ fusion with halo fixation can be used to supplement your fusion. Interspinous process wiring and anterior fixation may also be considered.

If poor screw purchase is encountered within the lateral mass, the use of a larger-diameter salvage screw may offer greater purchase. In the case of a fractured lateral mass, conversion to a Roy-Camille technique or cervical pedicle screws (C7) may also be considered. In the Roy-Camille technique, the starting hole is placed in the middle of the lateral mass. On the axial projection, the screw diverges approximately 10 degrees from the parasagittal plane. On the lateral projection, the screw trajectory is perpendicular to the posterior cortex of the mass.

Pitfalls

- Inadequate lateral mass size (C7)
- Poor fixation
- Vertebral artery violation
- Nerve root injury
- Injury to the adjacent facet joints

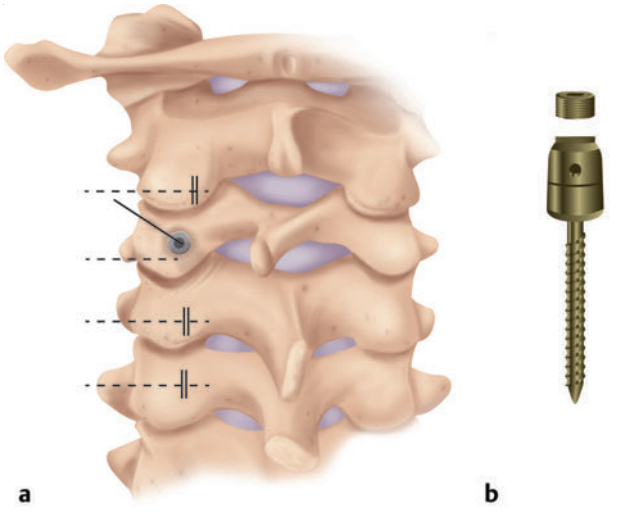

Fig. 10.1 **(a)** The portal of entry for the lateral mass screws should be in the middle of the lateral mass in the cephalad-caudad plane and 1 mm medial to midline in the medial lateral plane. **(b)** A lateral mass screw.

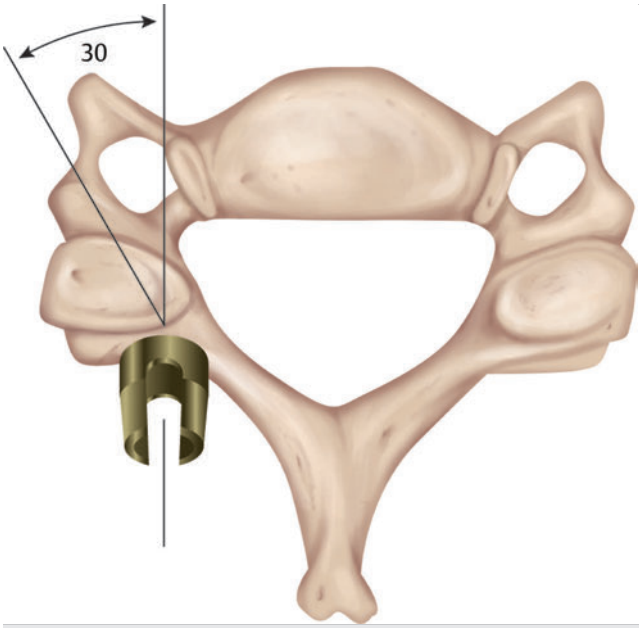

Fig. 10.2 The angle of insertion in the coronal plane should be 30 degrees from the sagittal plane. This limits the incidence of vertebral artery injury.

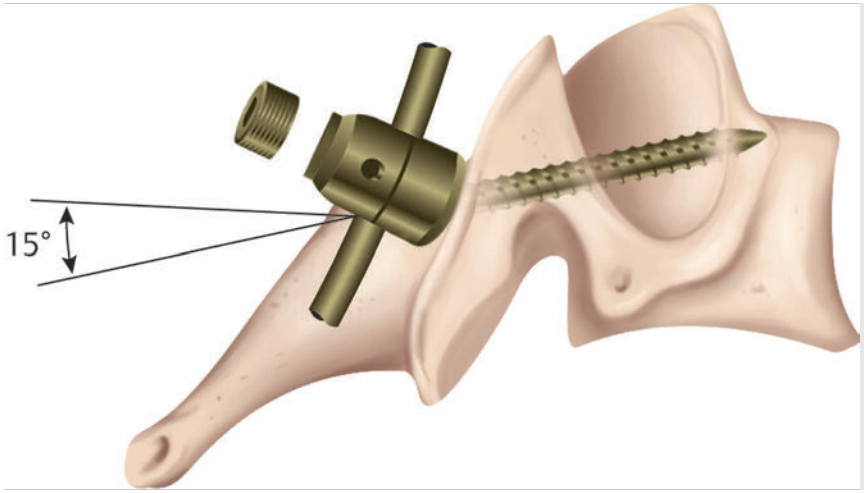

Fig. 10.3 The screw should be aimed 15 degrees cephalad relative to the vertebral body to avoid violation of the facet joint.

11 Cervical Subaxial Transfacet Screw Placement

John D. Koerner, Jeffrey M. Spivak, and Alexander R. Vaccaro

11.1 Description

This fixation technique is not commonly used as there are very few clinical series of posterior cervical fusions reported using this method alone. However, this technique can be quite useful for isolated facet joint fusions, and has been described as a salvage technique in cases of failed lateral mass fixation, as well as revision or deformity cases where normal anatomy may be altered.

11.2 Key Principles

A full understanding of the anatomical orientation of the cervical subaxial facet joints is imperative for the proper use and execution of this fixation technique. The cervical facet joints are flat and angled cephalad at approximately 60 degrees in the coronal plane.

Standard techniques for lateral mass screw insertion involve directing the screw path laterally and cephalad, avoiding any penetration of the facet joint. Subaxial transfacet screw fixation requires a caudal direction of the screw, perpendicular to and therefore across the facet joint surface.

11.3 Expectations

Transfacet screw fixation can be used as an isolated fixation technique, or more commonly as a supplementary method of fixation in combination with anterior plate fixation following anterior diskectomy or corpectomy. The technique is technically demanding, with little room for error, but it can be used to salvage inadequate lateral mass fixation. Biomechanical data have shown that transfacet screw placement provides stronger resistance to pullout than bicortical lateral mass screws, with the most pronounced difference noted at the C7–T1 level. This is likely due to the ability to cross four cortices with transfacet screws versus bicortical lateral mass screws. Transfacet screws have been found to have similar stability to lateral mass screw and rod constructs, as well as to lateral mass plates in flexion, extension, torsion, and lateral bending. Another potential benefit is the lower implant profile associated with transfacet screws versus lateral mass screw and rod constructs.

11.4 Indications

Use of subaxial facet screw fixation is indicated as an adjunct to cervical spine fusion. The technique can be used to support an anterior decompression and fusion procedure or as an isolated posterior fusion. It can be used in conjunction with other posterior fixation techniques including spinous process wiring and sublaminar wiring when these posterior elements are available. The technique can also be used as part of a multilevel posterolateral fixation construct in combination with lateral mass or pedicle fixation using rod or plate longitudinal members. It is very useful as a salvage technique for failed lateral mass fixation (▶ Fig. 11.1).

11.5 Contraindications

Use of subaxial facet screw fixation is contraindicated in cases where one or both of the lateral masses is comminuted, incompetent, or disconnected from the remainder of the vertebra, secondary to either a traumatic or neoplastic process. In cases requiring decompression of the neural foramen posteriorly via partial facetectomy and foraminotomy, this technique is not likely to be suitable due to the smaller amount of remaining facet joint surface following the decompression. Also, this technique should not be used for correcting deformity.

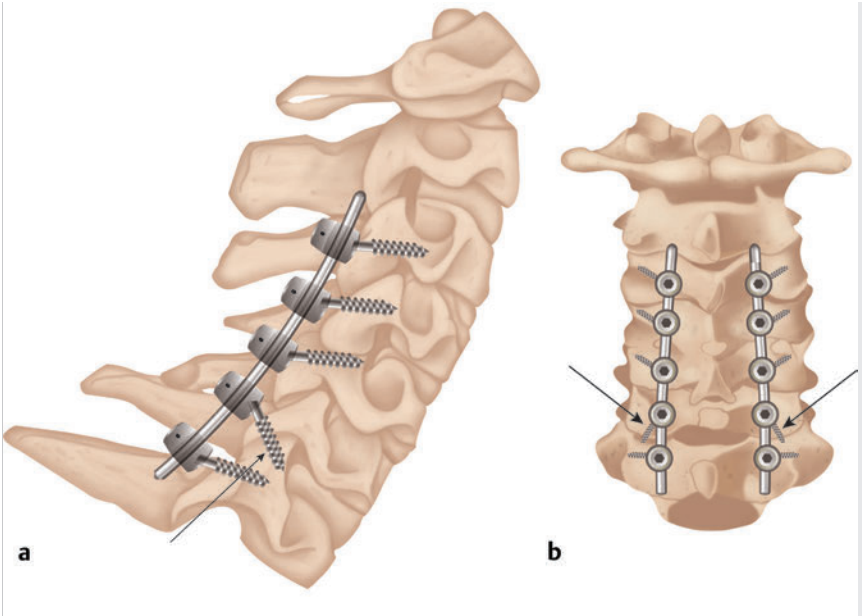

Fig. 11.1 **(a)** Lateral view and (**b**) posteroanterior view of transfacet fixation at C6–C7 as a salvage for failed right C6 lateral mass fixation. The caudal screw fixation (arrows) can be seen well in both views.

11.6 Special Considerations

For cases requiring fusion due to trauma or neoplasm, preoperative evaluation with computed tomography (CT) scanning including sagittal reconstructions is necessary to assess the bony integrity of the lateral masses and facet joint to be sure that posterolateral fixation of any type is a viable option for providing stability.

11.7 Special Instructions, Positioning, and Anesthesia

Prone positioning with rigid hold of the head using skull pin fixation is recommended. Adequate cervical alignment should be achieved before the skin incision if possible. If not, intraoperative reduction and realignment must be achieved before screw placement. Subaxial cervical facet screws are used only for fixation, not for segmental realignment.

11.8 Tips, Pearls, and Lessons Learned

Fluoroscopic guidance for screw placement is extremely useful to be sure that the joint is crossed near its midportion and to ensure adequate surrounding bone stock to avoid iatrogenic facet fracture. Fluoroscopy is also helpful to ensure that the next caudal facet joint is not disrupted at its anterior aspect due to too-caudal screw angulation.

Fluoroscopic visualization by level without parallax is important to ensure proper screw insertion. The left and right facet joints at each level should be visualized as one structure without incongruent overlap. Deformities of the motion segment can be compensated for by adjusting the position of the operative table or the fluoroscopy unit to visualize the facet joints properly. The alignment of the facets should be visualized and evaluated preoperatively once the patient is positioned and before prepping, draping, and beginning the procedure.

Use of a transfacet screw as part of a multilevel lateral mass fixation construct will place the screw-head offset from the regular lateral mass screw head positioning within the plate. This may require some compromise of optimal screw insertion point and angulation to keep it within the plate construct. Multiaxial screw and rod systems, with increased flexibility for screw-head position and screw angulation, are preferred for this type of mixed fixation construct.

11.9 Difficulties Encountered

The main difficulty with this type of screw placement is achieving adequate fixation across the facet joint. Use of intraoperative lateral fluoroscopy is extremely helpful to ensure proper trajectory and screw length. The tip of a small instrument may be placed into the joint space to become oriented to the facet joint alignment. At the upper levels of the subaxial cervical spine, the occiput may impede screw placement. Flexion of the head into the military tuck position may provide more room for instrumentation.

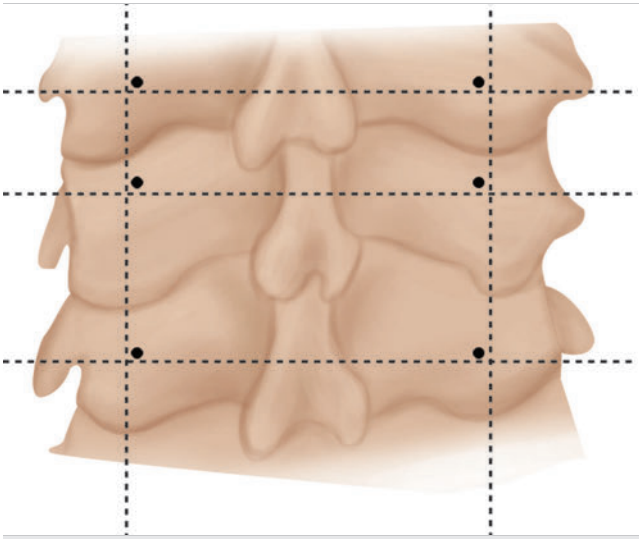

Fig. 11.2 Starting point for transfacet fixation is 1 mm medial and 1 to 2 mm cephalad to the midportion of the lateral mass.

11.10 Key Procedural Steps

As with cervical lateral mass screws, exposure of the posterior neck should allow for full definition of the lateral border of the lateral mass and the posterior aspect of the facet joint to be bridged. This joint capsule should be removed and the posterior facet decorticated, but the capsules of the joints above and below must be meticulously maintained if they are not to be fused.

The proper screw insertion point for a cervical transfacet screw is described as 1 mm medial and 1 to 2 mm cephalad to the midportion of the lateral mass (▶ Fig. 11.2). A starting point that is too lateral and inferior may be more likely to cause a facet fracture. The screw path is directed as perpendicular as possible to the facet joint, approximately 40 degrees caudally from the posterior lateral mass surface, and 20 degrees laterally to avoid the exiting nerve root and transverse foramen (▶ Fig. 11.3); 3.5-mm-diameter cortical bone screws are utilized, which is a standard size in most manufacturers' cervical screw-rod and screw-plate sets. Screw length should allow for fixation across the anterior cortex of the caudal lateral mass, typically 15 mm, but may be longer in upper cervical levels (C3–C4 and C4–C5) and shorter in lower cervical levels (C5–C6 and C6–C7). A screw angled too far medial will place the vertebral artery or exiting nerve root at risk, and a screw angled too lateral may miss the inferior lateral mass or cause a fracture. A trajectory too cephalad may also fail to engage the inferior lateral mass. On the lateral fluoroscopic view, the screw tip should end at or just past the posterior aspect of the vertebral body.

11.11 Bailout, Rescue, and Salvage Procedures

This technique is most commonly used itself as a bailout for failed segmental lateral mass fixation. When it is used as such and fails, as by fracture of the inferior articular process, the only potential monosegmental bailout would be the use of pedicle

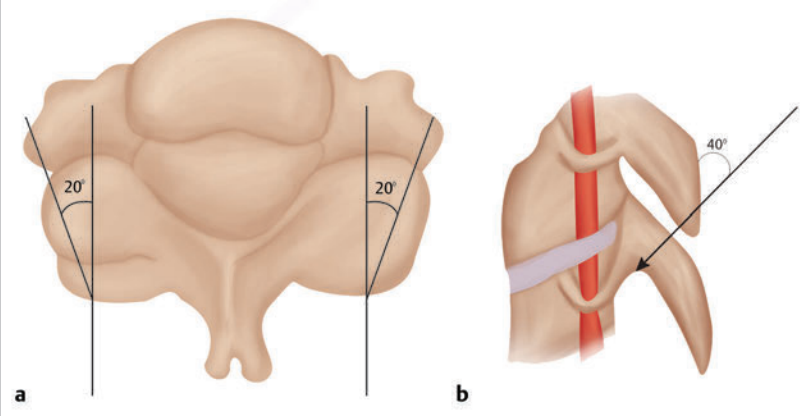

Fig. 11.3 Trajectory of transfacet screw is (**a**) 40 degrees caudally from the posterior lateral mass surface and (**b**) 20 degrees laterally.

screw fixation. Connection of pedicle screws to lateral mass or transfacet screws requires the use of offset connectors and rod-based systems, and cannot be done as part of segmental plate fixation. Additional lateral mass fixation used above or below a transfacet screw often provides adequate additional fixation along with onlay bone grafting.

Failure of this technique when using a primary procedure for monosegmental fixation may be salvageable with the use of lateral mass fixation if adequate bone stock is available, or by pedicle screw fixation if the surgeon has adequate experience with this technique in the midcervical spine. Fixation and fusion of additional levels above or below is also a potential salvage technique. Fixation of the contralateral side, with or without midline (spinous process) fixation, may also be sufficient and obviate the need for inclusion of any additional levels.

Pitfalls

- The caudal trajectory of the subaxial facet screw may get in the way of surrounding lateral mass screws. The head of a cephalad lateral mass screw may interfere with transfacet screw preparation and insertion, and may be so close together when inserted that rod insertion is problematic. The caudal transfacet screw may interfere with the optimal trajectory of a suprajacent lateral mass screw. To prevent this, the most caudal transfacet screw should be placed first, as the caudal end of the fixation is most prone to failure.

12 Cervical Pedicle Screw Placement

Jenna Robbins, Alexander T. Brothers, Arash Emami, and Sina Pourtaheri

12.1 Description

The proper technique for cervical pedicle screw placement aims to safely insert a screw into the cervical pedicle while avoiding damage to neighboring neurovascular structures and maximizing fixation.

12.2 Key Principles

Cervical pedicle screws deliver superior fixation and possess nearly double the pullout strength of lateral mass screws.

12.3 Expectations

Cervical pedicle screws are primarily employed for C2 and C7 fixation. Placing pedicle screws at other subaxial levels is less common and carries a high risk for injury to the vertebral artery. If the preoperative computed tomography (CT) and magnetic resonance imaging (MRI) scans have been thoroughly reviewed for the pedicle's morphology and the location of the adjacent neurovascular structures, pedicle screws can be safely placed with excellent fixation.

12.4 Indications

- Cervical, occipitocervical, or cervicothoracic instability
- Cervical kyphosis
- Incompetence of the cervical lamina or lateral mass from fractures, osteoporosis, or tumor destruction where other fixation methods are not possible; e.g., lateral mass screws, interlaminar screws, or sublaminar wires

12.5 Contraindications

- Absent, abnormally small, or destroyed pedicles
- Abnormal vertebral artery anatomy

12.6 Special Considerations

Computed tomography may be used preoperatively to determine bony anatomy and screw trajectory. Three-dimensional CT reconstructed images illustrate accurate morphology of the pedicles, especially in dysplastic instances. The relative location of the vertebral arteries in respect to the pedicle can be determined with MRI and magnetic resonance angiography. Furthermore, these imaging sequences identify the patency of the vertebral artery on either side, which is particularly important in acute fractures and tumor cases. The status of the vertebral artery on either side can change the operative management. Additionally, the vertebral artery is present in the foramen transversarium of C7 in 5% of the population.

12.7 Special Instructions, Positioning, and Anesthesia

Using a Mayfield holder, place the patient in a prone position. Adjust the shoulders for proper lateral fluoroscopy imaging by pulling shoulder girdles caudally while avoiding a brachial plexopathy.

12.8 Tips, Pearls, and Lessons Learned

Determine the trajectory, depth, and sagittal entry point of the screw with intraoperative lateral fluoroscopy. Often, the lateral fluoroscopic images are inadequate for the C7 pedicle due to the position of the shoulders. In such instances, the borders of the pedicle can be palpated with a probe after performing a laminoforaminotomy. Alternatively, accurate screw placement can also be accomplished with the proper use of bony landmarks. Another helpful adjunct is the anteroposterior (AP) intraoperative fluoroscopic image. The pedicles of C7 are easier to see on the AP than the lateral images. The AP fluoro view will confirm that the starting point is on the lateral border of the pedicle. Additionally, when advancing through the pedicle on the AP image, one can indirectly assess if the lateral-to-medial angulation is appropriate. If one has only tapped a short distance through the pedicle, but is on the medial border of the pedicle on the AP film, then the angulation is too medial and the trajectory should be redirected with less medial angulation. Furthermore, on the AP image one can indirectly assess superior-to-inferior angulation by assessing where the tap is going in relation to the superior and inferior border of the pedicle on the AP image, without having to take a lateral image.

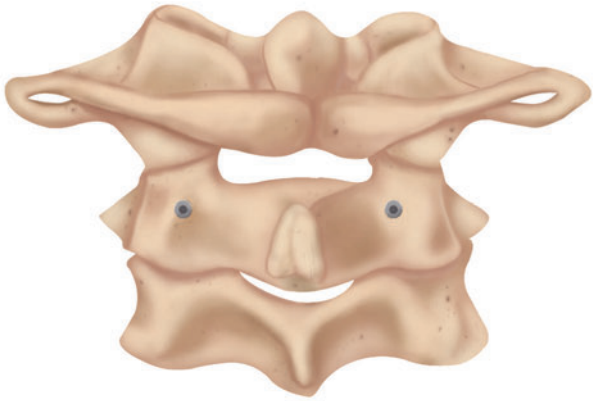

Fig. 12.1 Starting point of C2 pedicle screw.

12.9 Difficulties Encountered

In the case of a pedicle breach, consider using unilateral pedicle screw fixation with alternative fixation on the contralateral side (lateral mass screw, intralaminar screws, hooks, sublaminar wiring, or interspinous wiring).

12.10 Key Procedural Steps

12.10.1 Placement of C2

Begin by placing the C2 pedicle screw in the cranial medial portion of the C2 lateral mass (▶ Fig. 12.1). Consider palpating the medial border of the C2 pedicle and isthmus to confirm trajectory. Create an entrance hole in the lateral mass of C2 with a bur. Now tap the pedicle through this pilot hole in the appropriate trajectory: angle 15 to 20 degrees medially in the horizontal plane (▶ Fig. 12.2) and perpendicular to the anterior surface of the axis (▶ Fig. 12.3). It is recommended to palpate with a pedicle probe before and after tapping to check for breaches. Measure the depth of the hole tapped. The screw may engage the ventral cortex of C2 for better pullout strength. Place the screw in the same trajectory that it was tapped.

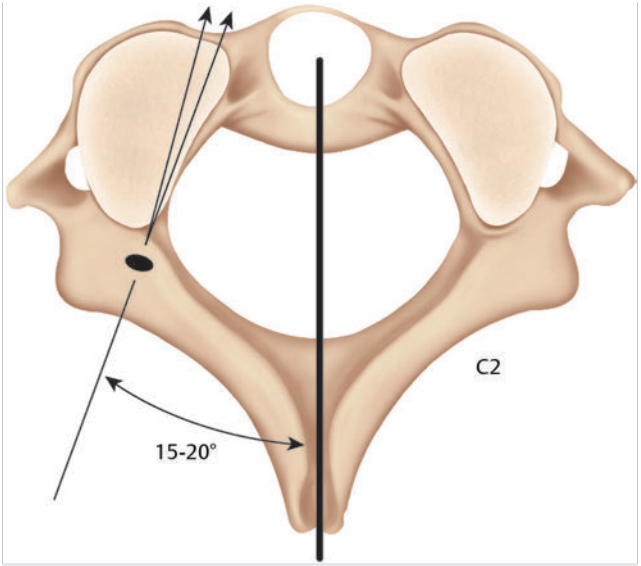

Fig. 12.2 C2 screw direction in the horizontal plane.

12.10.2 Placement of C3–C7

The C3–C7 vertebrae have a notch at the level of the pedicle in the lateral margin of the lateral mass. Insert the screws 3 to

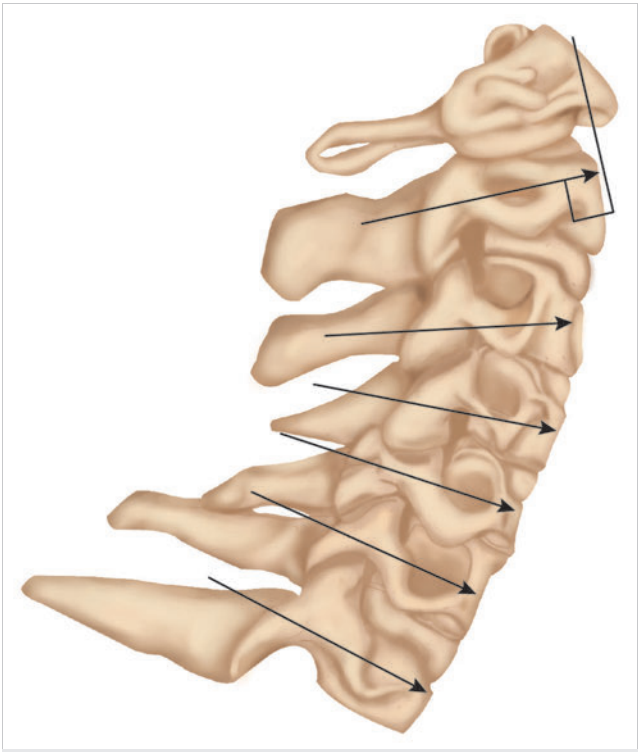

Fig. 12.3 Screw direction in the sagittal plane.

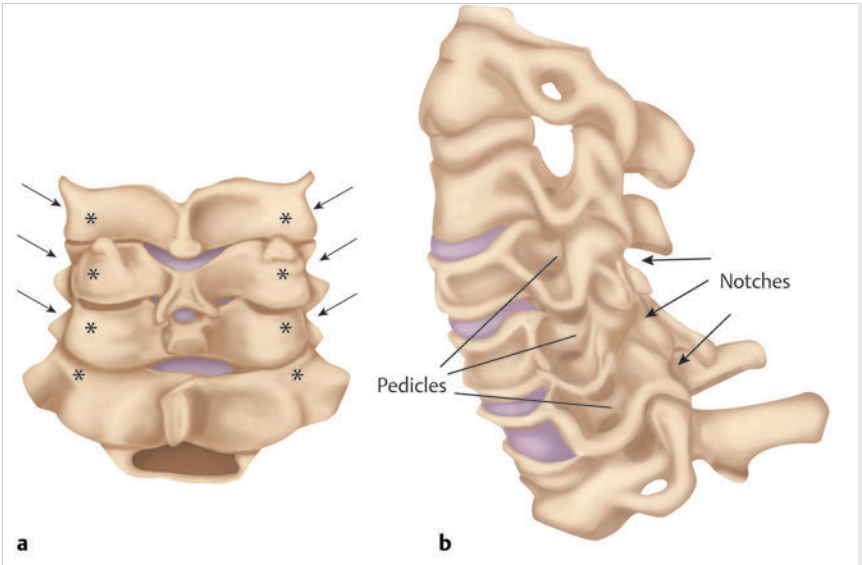

Fig. 12.4 **(a)** Starting points of C3–C7 pedicle screw placement. Each arrow indicates a notch on the lateral margin of the lateral mass. Asterisks show the screw starting points. **(b)** Lateral view of notches and pedicles.

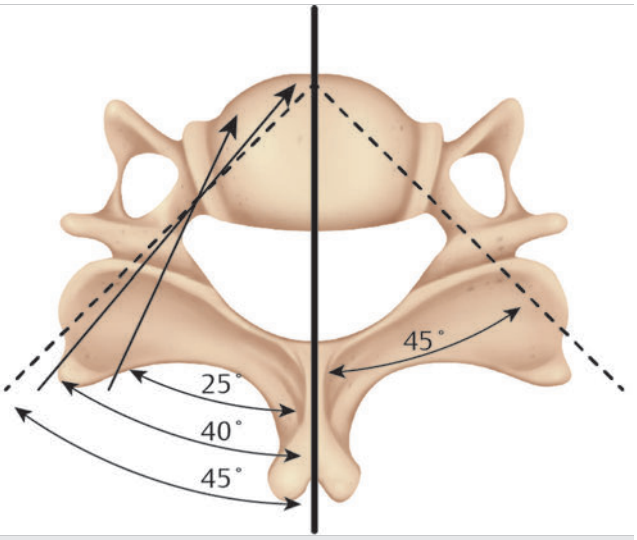

Fig. 12.5 C3–C7 screw direction in the horizontal plane.

4 mm medial to this notch while remaining lateral to the center of the lateral mass and below the inferior articular process of the cephalad vertebra's inferior margin (▶ Fig. 12.4). Medially angle the screw within the pedicles of C3 to C6 between 40 to 50 degrees in the horizontal plane. In the pedicle of C7, medially angle the screw 30 to 40 degrees. The screws may be placed less medially than the anatomical angle (▶ Fig. 12.5). The screws at C3 and C4 should angle in a slightly cephalad orientation in the sagittal plane, but remain neutral in the C5–C7 pedicles (▶ Fig. 12.3).

12.11 Bailout, Rescue, and Salvage Procedures

If the vertebral artery is violated, fill the hole with bone wax for hemostasis. However, if this does not provide hemostasis, consider inserting the pedicle screw to tamponade the bleeding. A third option is consulting interventional radiology for hemostasis. On the injured side consider a lateral mass screw or wiring (sublaminar or interspinous) to avoid bilateral vertebral artery injury. If the fixation is insufficient, then consider a rigid orthosis postoperatively or extending the fixation cranially and caudally.

Pitfalls

- Vertebral artery injury
- Nerve injury
- Breach of the pedicle cortex
- An inadequate pedicle size

Section III

Anterior Cervical Decompression

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III

13 Cervical and Thoracic Translaminar Screw Fixation

William E. Neway III, Deepak Joshi, and Peter G. Whang

13.1 Description

Translaminar screws are placed in the cervical and upper thoracic spine while avoiding injury to surrounding neurologic and vascular structures. Translaminar fixation may be safer than pedicle screws in the cervical spine because there is a lower risk of injury to the vertebral artery.

13.2 Key Principles

For translaminar screws to be effective, the vertebral body must have an intact pedicle because there must be continuity of the posterior elements with the vertebral body. Translaminar screws placed in the upper thoracic spine have been shown to have an equivalent or superior biomechanical profile relative to pedicle screws at these levels.

13.3 Expectations

This technique is expected to be used as a primary fixation technique at lower cervical and upper thoracic spine in children with small or dysmorphic pedicles. It can be used as a good bailout technique for failed pedicle or lateral mass screw fixation. This method can also be used as part of a hybrid construct for long posterior fixation constructs extending to the lower cervical and upper thoracic spine.

13.4 Indications

Translaminar screws can be used as fixation points in the cervical and upper thoracic spine, particularly in pediatric patients or in other instances where the pedicles are hypoplastic (e.g., neurofibromatosis).

13.5 Contraindications

- Fractures of the lamina, lateral mass, or pedicle
- Absence or other anatomical abnormalities involving the posterior elements
- Children < 4 years of age.

13.6 Special Considerations

A preoperative computed tomography (CT) scan is necessary to delineate the bony anatomy and determine if screws can be inserted into both laminae and is beneficial for planning the screw trajectories. In general, it may be difficult to obtain bilateral fixation in the upper to midcervical spine (i.e., between C3 and C6).

13.7 Special Instructions, Positioning, and Anesthesia

The patient is placed in the prone position with the head secured in a Mayfield head holder. The shoulders should also be retracted caudally to facilitate intraoperative visualization of the lower cervical spine.

13.8 Tips, Pearls, and Lessons Learned

For bilateral screw placement, the entry point must be adjusted caudiocranially to allow for both screws to be inserted, but not so far from the middle of the lamina to cause a cortical breach. The entry point of the caudal screw must be placed close to the caudal margin of lamina near the spinolaminar junction, or it may preclude placement of the second screw. The use of a hand drill may be useful for minimizing the risk of cortical breach. Depending upon the anatomy measured from the preoperative CT, the diameter of the screws is typically 3.5 or 4 mm.

13.9 Difficulties Encountered

- As the ventral wall of lamina is not directly visualized, there is a possibility that screw may pass too ventrally into the spinal canal which could potentially result in an injury to the spinal cord.
- It may not be feasible to place two screws in opposite directions through relatively small laminae.
- In obese patients, it might be difficult to obtain the proper trajectory (i.e., 40–45 degrees relative to the vertical plane) because of the depth of the surgical wound.
- If the screw length is too long, it is possible that the tip may violate the contralateral facet joint.

13.10 Key Procedural Steps

The entry point for the screw is located at the junction of the spinous process and the lamina. A bur is used to create a pilot hole so that a drill or small pedicle awl may be introduced between the inner and outer cortical tables in line with the angle of the lamina, aiming for the junction of the transverse process and superior facet that will reduce the risk of entering the contralateral foramen. The tract is palpated with a ball-tipped probe to ensure no breach is present and tapped if necessary prior to insertion of the screw.

13.11 Bailout, Rescue, and Salvage Procedures

In the case of a dural injury causing a cerebrospinal fluid (CSF) leak through the entry hole, bone wax may be placed to tamponade the leak; if warranted, a portion of the lamina may need to be removed to allow for a dural repair. If the screw purchase is suboptimal or a fracture of the lamina occurs, alternative fixation methods may be needed (e.g., transpedicular screws, hooks, or sublaminar wiring). In situations where the construct is still unstable, the fusion may be extended to include additional levels and more rigid types of external immobilization may be considered.

Pitfalls

- It might not be possible to place even a unilateral translaminar screw at C4 or C5 due to the small size of the lamina thickness at these levels.
- A unilateral translaminar screw has lesser pullout strength than a pedicle or lateral mass screw.
- Placing the entry point in the middle of the rostral-caudal aspect of the spinous process may not leave adequate room for the contralateral screw to pass by.
- Placing the entry point too dorsally or ventrally may lead to unsatisfactory screw placement.
- Drilling past the far end of the lamina could result in injury to the facet joint or even the vertebral artery.
- Unrecognized ventral breach into the spinal canal could result in dural laceration, CSF leak, or even injury to the spinal cord.

14 Transoral Odontoid Resection and Anterior Odontoid Osteotomy

Amgad Hanna, Carolina Sandoval-Garcia, and Praveen Deshmukh

14.1 Description

The transoral procedure uses an anterior midline approach through the oropharynx to gain access to the anterior craniocervical junction.

14.2 Key Principles

The transoral approach remains the procedure of choice for anterior decompression of pathologies involving the craniocervical junction. In general, it provides potential access to the lower clivus down to the lower border of C2.

Disadvantages include mainly traversing the oral cavity with risk of contamination with oral flora resulting in increased risk of infection and complications related to airway and feeding, including the need for prolonged intubation / tracheostomy or placement of enteral feeding tube. Another possible risk is affecting phonation in cases where there is extensive soft palate splitting and hard palate resection. Mandibular splitting procedures may be required to increase exposure.

14.3 Expectations

This procedure, combined with posterior stabilization, provides decompression and stabilization of craniocervical pathology and allows immediate mobilization in a cervical collar with a low surgical morbidity. Careful selection of candidates is important. As with all surgical patients, for those with poor health, optimization of preoperative nutritional status is essential. Nasopharyngeal incompetence is a frequent postoperative finding, but typically recovers in a delayed manner.

14.4 Indications

- Inflammatory conditions like rheumatoid arthritis with spinal compression symptoms and irreducible anterior neuraxial compression at the craniocervical junction (▶ Fig. 14.1). The compression could be due to a soft tissue mass (pannus) or vertical migration of the dens (▶ Fig. 14.2). Other inflammatory conditions include calcium pyrophosphate dihydrate (CPPD) disease or pseudogout.
- Degenerative conditions leading to basilar invagination
- Irreducible chronic nonunion of a fractured odontoid process
- Extradural tumors, e.g., chordoma
- Intradural lesions: meningiomas, schwannomas, neurenteric cysts when a far lateral approach is not feasible
- Rarely for vascular pathology, aneurysm clipping (vertebrobasilar), when these lesions are low and cannot be approached endovascularly or posterolaterally

14.5 Contraindications

- Dental or periodontal abscess
- Reducible lesions; need only posterior stabilization, without decompression
- Inability to open the mouth > 25 mm, which could be due to associated temporomandibular joint disease. This is a relative contraindication; these lesions can be approached through a transmandibular approach.

14.6 Special Considerations

- There is a potential for instability after this procedure due to resection of the anterior osseous and ligamentous structures. Although some people do not routinely perform posterior

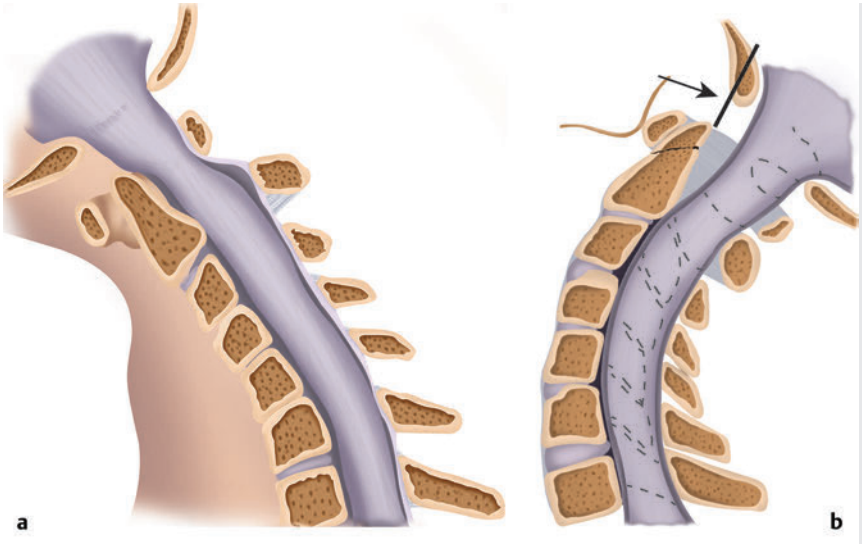

Fig. 14.1 Representations of preoperative plain radiographs in flexion **(a)** and extension (**b**) in a patient with rheumatoid arthritis, revealing C1–C2 instability, which reduces in extension.

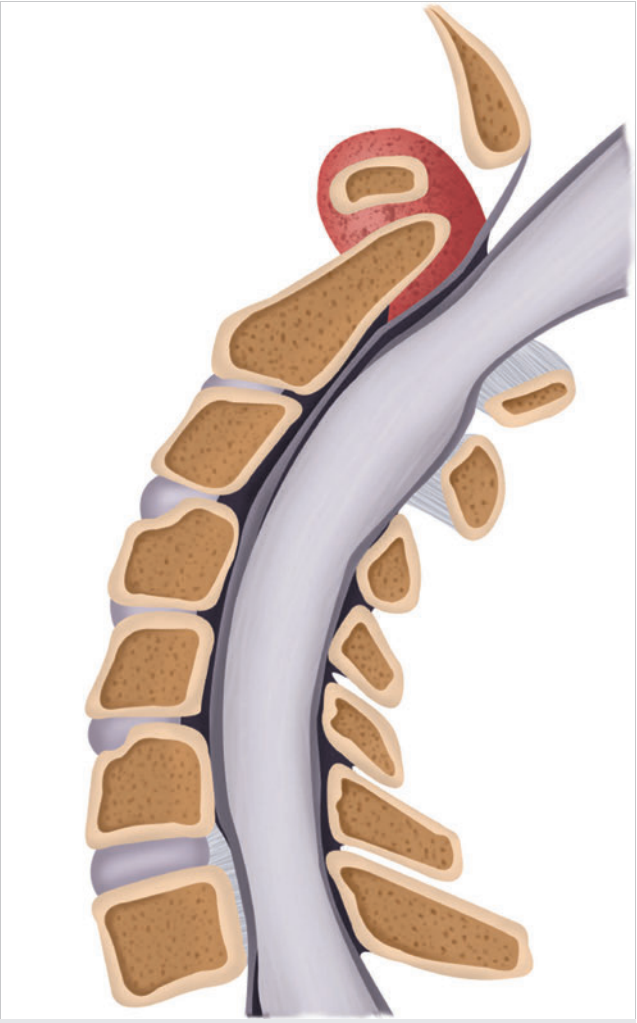

Fig. 14.2 Representation of a preoperative sagittal T2-weighted magnetic resonance image showing compression of the cervicomedullary junction by a rheumatoid pannus.

internal fixation, we recommend posterior arthrodesis as an adjunct to this procedure.

- The vertebral arteries are 24 mm from the midline at the arch of C1, 11 mm from the midline at the foramen magnum, and at the C2–C3 junction. However, this anatomy could be distorted by pathology or congenital abnormalities.
- Patients with irregular dentition may require a gum guard to be fashioned prior to surgery to fit the retractor and the dentition. We have used the Aquaplast flat guard ivory squares (Shippert Medical Technologies). Edentulous patients may require special adjustments in the retractor to avoid slippage during the procedure.

14.7 Special Instructions, Positioning, and Anesthesia

- A high-resolution CT scan should be obtained to clearly delineate the bony anatomy.
- Preoperative magnetic resonance imaging (MRI)/magnetic resonance angiography helps plan the procedure by identifying the degree of compression, the anatomy and dominance of the vertebral arteries, and the relationship of the internal carotid arteries to the anterior arch of C1.
- Positioning recommendations include supine position, with neck in slight extension and head placed in three-point skull fixation system like a Mayfield head holder.
- Topical hydrocortisone ointment (1%) to the oral cavity before and after surgery reduces significantly the amount of perioral swelling.
- Somatosensory and motor evoked potentials should be considered to monitor spinal function during positioning and surgery.
- Intraoperative guidance could be achieved by fluoroscopy, intermittent intraoperative X-ray imaging, or image-guided intraoperative navigation. These adjuncts as well as endoscopy are useful particularly in cases of tumor or extensive lesion resection where some distortion of the normal anatomy is present.
- A nasogastric tube helps to prevent postoperative wound contamination. The tube should be left in place for enteral feeding during the first few days postoperatively until satisfactory swallowing function is regained. Usually, diet is advanced slowly after 1 week.
- The endotracheal tube should be left in place for 24 to 48 hours after surgery, or until the surgeon is sure that the airway is not compromised.
- Postoperative palatal dehiscence should be immediately closed, whereas late (> 1 week) postoperative pharyngeal dehiscence is better left to granulate because of friable edges with diversion of particulate food via the nasogastric tube or gastrostomy. However, direct repair may be attempted in early postoperative pharyngeal dehiscence.

14.8 Tips, Pearls, and Lessons Learned

- If the interdental distance is ≥ 25 mm with mouth opening, the transoral approach is feasible.
- Perioperative antibiotics, usually cephalosporins, are used to decrease the rate of infection. The infection rate is also diminished by protecting the mucosal edges during the surgery to allow the apposition of cleanly incised healthy edges at the end of the procedure, obliterating the dead space by two-layer closure of the posterior pharyngeal wall, and avoidance of particulate food until the wound has healed.
- Release of the tongue retractor blade from time to time during the procedure helps to reduce postoperative swelling. The surgeon always needs to avoid catching the tongue between the patient's teeth and the retractor.
- Magnification is achieved by surgical loupes, operative microscope, or endoscopy.
- The anterior tubercle of atlas with the attached longus colli and anterior longitudinal ligament is an important landmark to the midline.
- The lateral exposure should not exceed 2 cm from the midline to avoid injury to the vertebral arteries, hypoglossal nerves, or eustachian tubes.
- A freely pulsating dura mater is a good sign of adequate decompression.

14.9 Difficulties Encountered

- Inability to open the mouth enough to do the operation can be enhanced by palatal or mandibular splitting. Better visibility could also be obtained using the endoscope.
- The biggest challenge is getting lost, especially for defining the midline, or the caudal extent of the decompression. One may use intraoperative fluoroscopy or navigation for better orientation.

14.10 Key Procedural Steps

Fiberoptic laryngoscopy with nasotracheal or orotracheal intubation is less hazardous than tracheostomy. However, tracheostomy is sometimes indicated, especially with preoperative brainstem dysfunction or persistent postoperative swelling. The transoral approach is typically performed with the patient in a supine position with the head slightly extended. Head extension moves the dens caudally into the operative field. The head is held in place either fixed in a Mayfield or a horseshoe headrest. The lateral position has been used by some surgeons to access both the mouth for decompression and the back for fusion. However, it presents the surgeon with unfamiliar anatomy, both from the front and the back. The mouth and oropharynx are prepared with 1% betadine or cetrimide. The upper esophagus is packed with a collagen sponge or gauze to minimize the ingestion of blood.

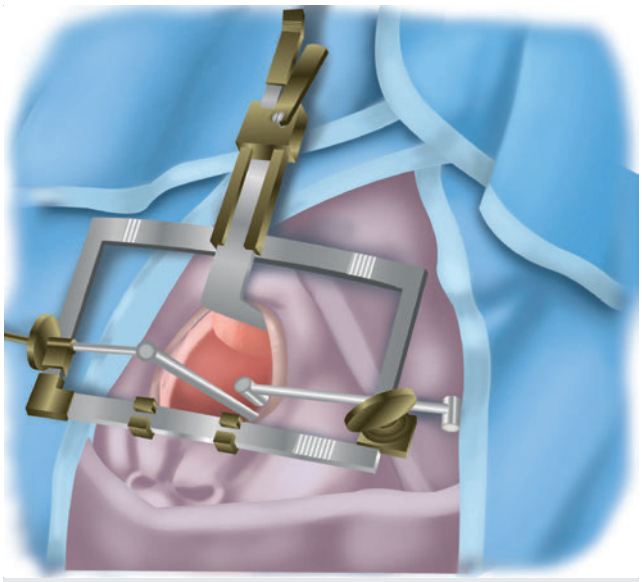

Fig. 14.3 Operative set-up, showing the positions of different members of the operative team. The operative microscope is brought in from behind the surgeon (at the head of the patient).

A right-handed surgeon stands at the patient's left side of the head, and anesthesia is placed at the foot of the table. The nurse stands in front of the surgeon to the left of the patient, and the assistant on the right side of the patient (▶ Fig. 14.3). An image intensifier can be brought in and positioned for a lateral view. The operating microscope is placed at the head of the patient. If navigation is used, the screen should be placed so that it is easily accessible to the surgeon, preferably in front of him. Special retractors are used for better visualization: Dingman, McIvor, Spetzler-Sonntag, or Crockard self-retaining retractor. The soft palate is retracted and sometimes needs to be divided for better exposure (▶ Fig. 14.4a). Uvular retraction is achieved by placing a suture through the uvula or suturing tubing to the uvula itself and pulling that through the nostril. Similarly, the soft palate can be retracted rostrally into the nasopharynx with transnasal rubber catheters.

If visualization below C2 is necessary, it may be necessary to split the mandible.

The posterior pharyngeal wall is infiltrated with 1% lidocaine with epinephrine. The posterior pharyngeal mucosa is incised in the midline using the anterior tubercle of atlas as a landmark. The muscles are then elevated from the anterior surface of the clivus, the anterior arch of C1, and the anterior surface of C2. Some surgeons recommend exposing laterally until the medial aspect of the C1–C2 joint is seen. About 14 mm of the anterior arch is removed to expose the dens and pannus (▶ Fig. 14.4b). This is achieved by a high-speed drill or Kerrison rongeurs. The odontoid is typically resected craniocaudal. The major part of the dens is removed using a 3-mm cutting bur; once it has been hollowed out, the posterior cortical bone is removed using a diamond drill or curettes and Kerrison rongeurs (▶ Fig. 14.5). An ultrasonic BoneScalpel (Misonix) can be used to perform bilateral cuts in the anterior arch of C1 and the base of the odontoid.

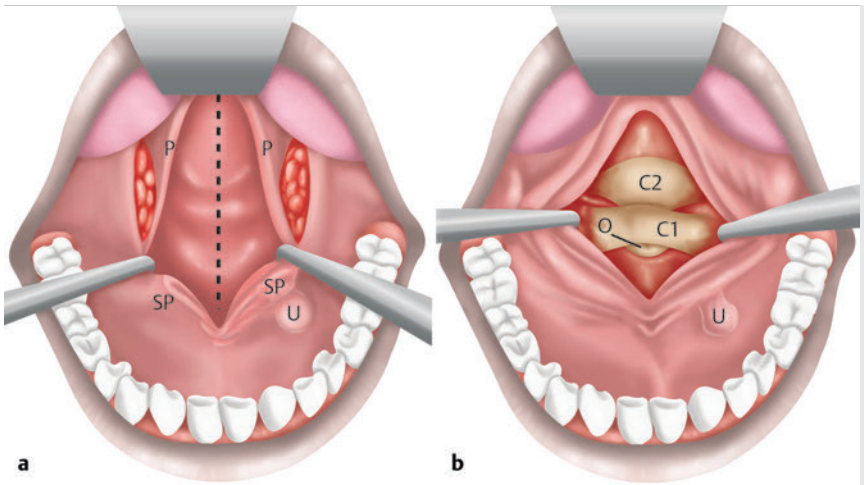

Fig. 14.4 (a,b) Intraoperative views after splitting the uvula (U) and soft palate (SP), and after incision of the posterior pharyngeal wall (P), and resection of the anterior arch of C1, revealing the odontoid process (O) of C2.

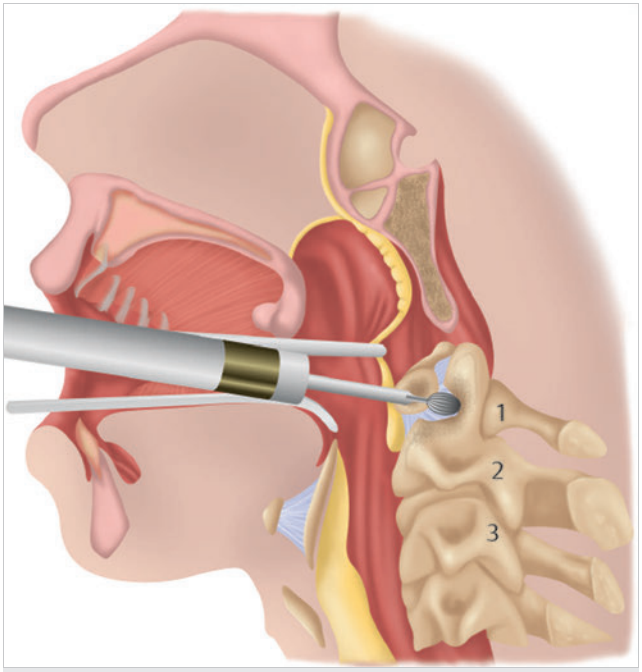

Fig. 14.5 Representation of an intraoperative fluoroscopic view of the final part of drilling of the dens. 1 = C1; 2 = C2; 3 = C3.

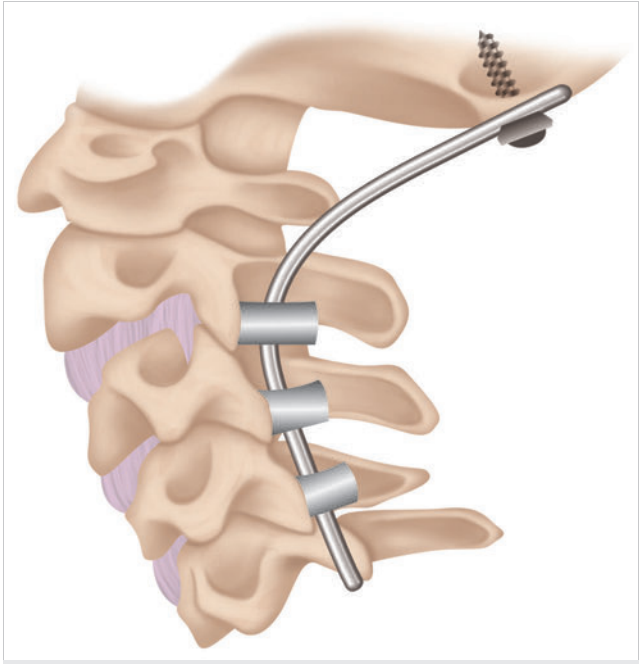

Fig. 14.6 Postoperative lateral view after anterior decompression and posterior craniocervical instrumentation.

It is usually hard to differentiate the ligaments from the inflammatory pannus. The osseous pannus and ligaments are dissected from the dural surface to achieve decompression. Bipolar coagulation, nerve hook, 2-mm angled curettes, 1- or 2-mm Kerrison rongeurs, and dissectors are used to aid in the decompression. Resection is continued laterally until the lateral curvature of the dural sac is identified and the dura is pulsating.

The introduction of transoral endoscopy could potentially reduce complications related to retraction and exposure. It has been shown to improve visualization although it makes the surgery technically more challenging especially during the learning curve. The endoscopic transnasal approach has also gained more popularity due to the minimal invasiveness and to avoid complications related to tongue retraction, palate splitting, and upper airway swelling. There are reported cases of anterior C1 ring preservation to avoid the need for posterior fusion. Altogether, continued advances in endoscopy will likely result in more frequent inclusion of this tool during transoral approaches.

Closure should be performed in layers: muscular and mucosal, with 3–0 or 4–0 absorbable sutures. If opened, the soft palate should be closed in two layers, the nasal mucosa with interrupted sutures and oral mucosa should be approximated with the muscularis. Special attention should be made to avoid tight suturing to prevent mucosal ischemia. Posterior stabilization should then be performed (▶ Fig. 14.6) or the patient is kept in a halo vest.

14.11 Bailout, Rescue, and Salvage Procedures

- Inadequate exposure cranially: Split the soft palate.
- Inadequate exposure caudally: Split the mandible.
- Vertebral artery bleeding can be controlled by packing. Bone wax can be used. Postoperative vascular studies (angiogram or CTA) may be necessary if vertebral artery injury is suspected. Venous bleeding can be controlled by Gelfoam (Pfizer Pharmaceuticals), SURGICEL (Johnson & Johnson), Avitene (CR Bard), or fibrin glue.
- Dural tears: We recommend using both fascial autograft (fascia lata), and artificial dural substitutes, with fibrin glue. The dural grafts tend to slide caudally; they should be stabilized with small clips in the corners. Postoperatively, the patient should be sitting up in bed. Lumbar drainage may not be necessary unless postoperative CSF leak is noted. (**Video 14.1**) shows preparation, positioning, and key procedural steps.

Pitfalls

- Failure to recognize or treat cerebrospinal fluid (CSF) leak could be complicated by meningitis that can be fatal.
- The internal carotid artery may have a variable relationship with the anterior arch of C1.

15 Anterior Cervical Diskectomy and Foraminotomy

Kern Singh, Steven J. Fineberg, and Benjamin C. Mayo

15.1 Description

Pathological processes, including trauma and age-related degeneration, may affect the cervical spine resulting in the clinical presentation of radiculopathy or myelopathy. Anterior cervical diskectomy and foraminotomy is an effective technique for neural decompression secondary to herniated disks and spondylotic spurs.

15.2 Key Principles

Adequate neural decompression via a diskectomy requires a precise annulotomy, thorough diskectomy, and meticulous foraminotomy.

15.3 Expectations

A thorough diskectomy and meticulous end plate preparation will allow for neural decompression, disk space distraction, and successful interbody graft incorporation.

15.4 Indications

- Failure of nonoperative treatment to relieve persistent or recurrent radicular arm pain
- Progressive neurologic deficit
- Myelopathy

15.5 Contraindications

- Bleeding disorders and posterior neural compression secondary to hyperlordosis
- Ligamentous infolding
- Osteophytic formation

15.6 Special Considerations

Preoperative imaging is essential to determine the etiologic and anatomical sites of neural compression. Plain radiographs, in addition to magnetic resonance imaging (MRI), and/or myelography and postmyelogram computed tomography (CT) imaging are essential for identifying sites of neural compression.

15.7 Special Instructions, Positioning, and Anesthesia

The operating room table should be placed into a slight reverse Trendelenburg position allowing for venous drainage. The neck may be extended by placing a small roll vertically between the scapulae. Caudal traction to the shoulders is gently applied using adhesive tape. Good lighting and the use of loupes or a microscope facilitates the diskectomy and decompression. Total intravenous narcotic anesthesia is utilized allowing for the measurement of somatosensory-evoked potentials, motor-evoked potentials, and dermatomal-evoked potentials in a specific nerve root distribution.

15.8 Tips, Pearls, and Lessons Learned

Anatomical landmarks may aid in the placement of the surgical incision. Typically, the hyoid bone overlies the C3 vertebral body, the thyroid cartilage overlies the C4–C5 intervertebral disk space and the cricoid ring lies at the C6 level. Disk space localization is performed with a radiopaque marker and a lateral radiograph (▶ Fig. 15.1). An anulotomy is then made outlining the disk end plate junction using a sharp scalpel. Curettes must always stay in the disk space while "peeling" the disk and end plate cartilage to avoid damaging the esophagus or other soft tissue structures (▶ Fig. 15.2). Perforation of the end plate should be avoided to minimize bleeding. A 3–0 angled curette is helpful for getting behind the uncinate process and for creating a path for the 1- and 2-mm Kerrison punch to resect the uncinate process. Adequacy of the foraminotomy can be determined by passing a nerve hook anterior to the exiting nerve root without significant resistance. Routine removal of the posterior longitudinal ligament is unnecessary and reports of postoperative epidural hematoma and other complications may occur with this technique.

Synthetic interbody cages are becoming utilized more frequently in place of autograft or allograft. Polyetheretherketone (PEEK) is a popular choice of biomaterials for these cages. PEEK cages have biomechanical properties that allow them to stimulate bone fusion while decreasing the stress shield effect at fusion sites. Stand-alone PEEK interbody cages may be utilized for single-level pathology. However, stand-alone cages are not recommended for use in multilevel surgery as fusion rates may decline with increasing number of levels.

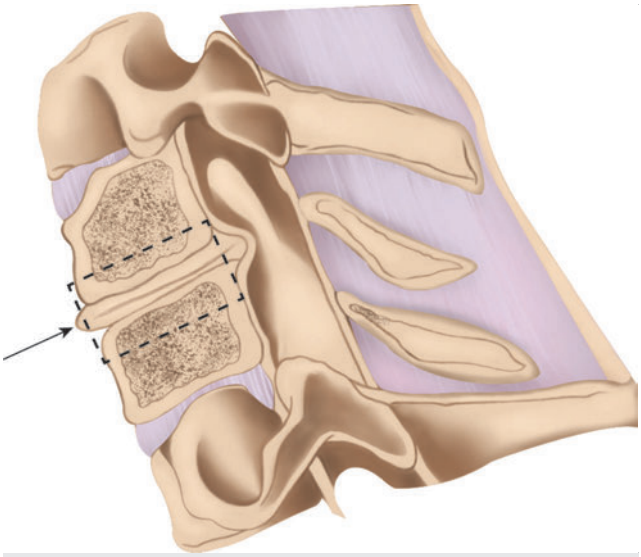

Fig. 15.1 Representation of a lateral radiograph of the cervical spine used for localization.

15.9 Difficulties Encountered

In cases of severe spondylosis, disk space visualization may be difficult. Osteophytes and the anterior inferior corner of the superior vertebra can be removed using an osteotome or a high-speed bur (▶ Fig. 15.3). This maneuver increases "the window" or space for adequate and safe removal of the disk. The use of sequentially larger curettes may help in disk extraction. A small Cobb may be twisted while positioned intradiskally to allow for distraction of the disk space and cracking of the posterior anulus.

15.10 Key Procedural Steps (Video 15.1)

- Soft tissue dissection
- Localizing lateral radiograph (▶ Fig. 15.1)
- Harvest bone graft (if allograft is not being used) while the X-ray is being taken (usually 9-mm tricortical graft)
- Sharp annulotomy and radical diskectomy with a scalpel and then an O-curette (▶ Fig. 15.2)
- 3–0 angled curette to palpate behind the vertebral body
- 1-mm followed by a 2-mm Kerrison punch to perform the uncinate resection
- Decortication of the end plates and contouring of the harvested bone graft, allograft, or placement of a synthetic interbody spacer (▶ Fig. 15.3)
- Repeat steps for any other disk space levels
- Place the plate across the prepared disk space to be fused (▶ Fig. 15.4)

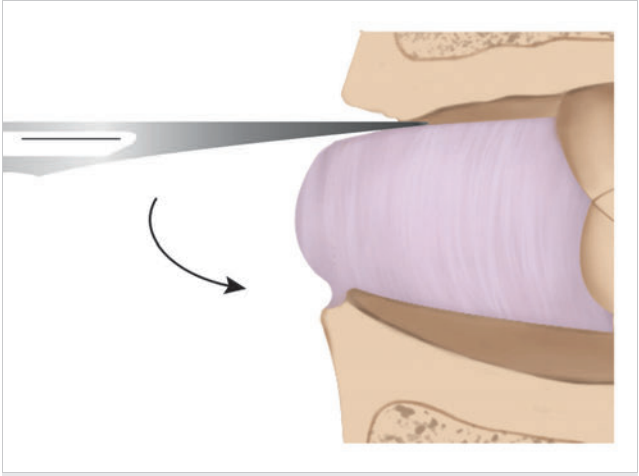

Fig. 15.2 Sharp anulotomy and radical diskectomy with a scalpel.

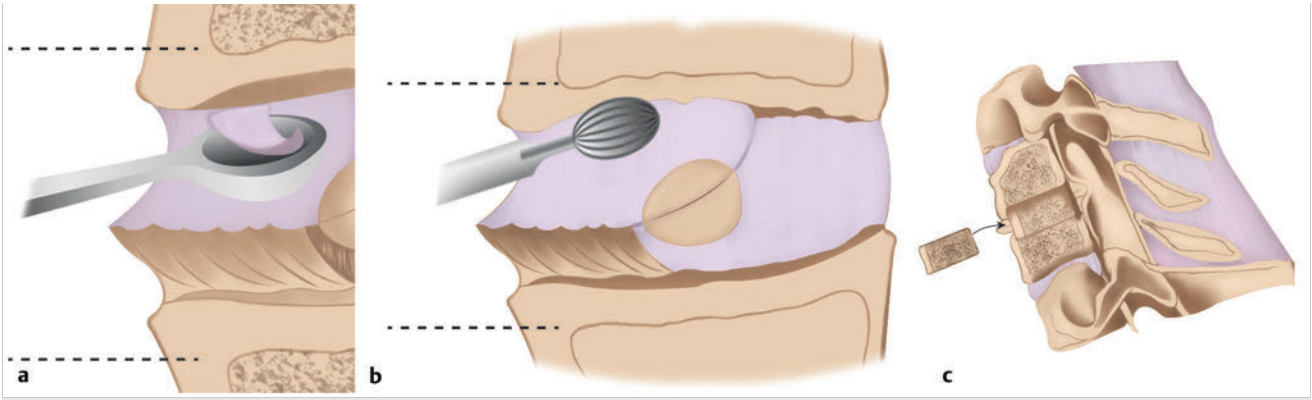

Fig. 15.3 **(a,b)** Decortication of the end plates and **(c)** contouring of the harvested bone graft.

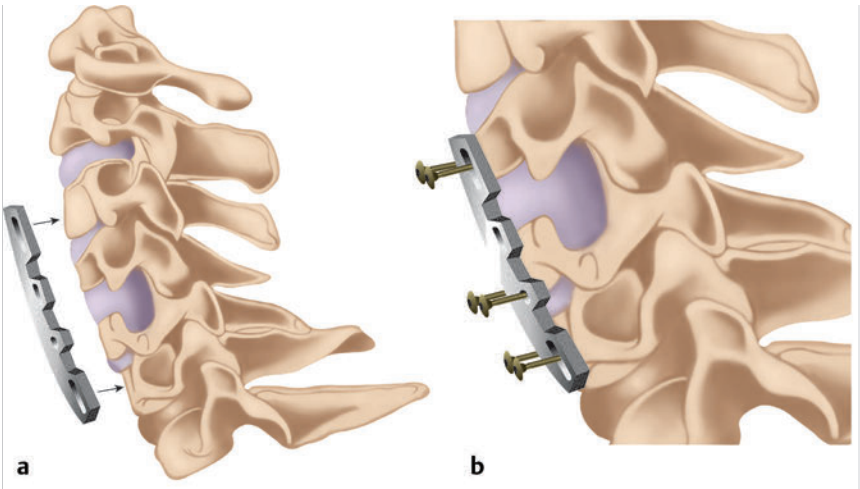

Fig. 15.4 **(a,b)** Placement of the plate across the prepared disk space that is to be fused.

15.11 Bailout, Rescue, and Salvage Procedures

Treatment of an inadequate decompressive foraminotomy may be achieved via a posterior foraminotomy versus a revision anterior foraminotomy. Pseudarthrosis may be treated by a repeat anterior diskectomy and interbody fusion or via a posterior arthrodesis.

Pitfalls

- The incidence of vocal cord paralysis from recurrent laryngeal nerve injury ranges from 1 to 11%.
- Possible etiologies include traumatic division, neurapraxia, compression from postoperative edema, and injury from thermal necrosis.
- Midline soft tissue injury to the trachea, esophagus, and pharynx are uncommon.
- Dysphagia following anterior cervical surgery is common, but temporary, and is estimated to occur transiently in 8% of patients.
- Vascular injuries may be prevented by avoiding overzealous retraction and by using blunt-edged retractors.
- The likelihood of pseudarthrosis may be minimized by performing a meticulous diskectomy and thorough decortication of the end plates.

16 Anterior Cervical Foraminotomy Technique

Peter Syre, Luke Macyszyn, Sarah Nyirjesy, Paul W. Millhouse, John D. Koerner, Alexander R. Vaccaro, and Neil R. Malhotra

16.1 Description

An anterior cervical foraminotomy can be performed when there are isolated single-level radicular symptoms, cervical spondylotic myelopathy, or compressive pathology without findings to support the need for complete diskectomy. In contrast to posterior foraminotomy, the anterior approach provides direct decompression of the nerve root and access to anterior osteophytes and free disk fragments with minimal nerve manipulation. Compared with complete anterior diskectomy, the anterior foraminotomy accomplishes direct decompression of the nerve root while preserving both motion and stability of the spinal segment. Cervical foraminotomy via an anterior approach permits removal of any offending bone spurs or compressive extranuclear disk material, thus reconstructing the normal anatomy of the neural foramen via direct visualization of the nerve root. Cervical foraminotomy can significantly improve disability with positive clinical outcomes, rapid recovery, and no need to wear a cervical orthosis.

16.2 Key Principles

Although cervical diskectomy effectively addresses the compression causing myelopathy, an anterior foraminotomy with complete decompression of the nerve root effectively addresses unilateral upper extremity radiculopathy while maintaining mobility of the affected segment.

16.3 Expectations

Decompression of the nerve root leads to excellent outcomes in the appropriately selected patient without a need for instrumentation or a postoperative cervical brace. The offending compressive pathology can be accessed and removed via foraminal exploration.

16.4 Indications

Indications are similar to those of anterior cervical diskectomy, specifically isolated unilateral radiculopathy, in conjunction with imaging that supports the finding of a free foraminal disk fragment or medially located osteophytes. This technique provides direct decompression and is also indicated for spondylotic stenosis and removal of spinal tumors. Conservative treatment for a minimum of 6 weeks is generally attempted before surgery, unless there is evidence of significant myelopathy or motor weakness, in which case a more extensive procedure may be indicated.

16.5 Contraindications

Anterior cervical foraminotomy is contraindicated in patients with myelopathy due to compression involving the entire disk or vertebral body. In these patients, an anterior cervical diskectomy and/or corpectomy and fusion is more appropriate. Anterior foraminotomy is also not indicated in the setting of posterior compression, midline compressive lesions, or in the presence of a significant spondylolisthesis.

16.6 Special Considerations

Preoperative imaging, including radiographs and magnetic resonance imaging (MRI) in conjunction with the physical exam and a description and location of the pain, permits tailoring of surgery to most benefit the patient. Flexion/extension radiographs should be performed if there is a question of instability. Computed tomography (CT) scans of surgical levels should be considered if other imaging does not adequately resolve questions concerning bony pathology.

16.7 Special Instructions, Positioning, and Anesthesia

The patient should always be counseled about the risk of sympathetic plexus injury and Horner-type syndrome, as well as hoarseness, cerebrospinal fluid leak, vertebral artery injury, and swallowing difficulties. Positioning is analogous to that for an anterior diskectomy. The patient is placed supine on the operative table with a gel roll under the scapulae (if there is no significant spinal canal compression) to aid in extension and exposure of the operative field. The head is kept straight and a foam doughnut or horseshoe headrest is placed under the head to enable maximal safe extension and minimization of jaw intrusion into the operative field.

Perioperative antibiotics should be administered 30 minutes prior to the skin incision. Intraoperative neurophysiologic monitoring may be used if the surgeon considers it appropriate. If so, baseline recordings should be established before positioning of the head and monitored throughout the surgery. The shoulders should be taped down to maximize cervical exposure and permit adequate cross-table lateral radiographs to be taken for localization. The arms should be well padded and tucked at the patient's side. After the initial dissection down to the anterior spine, an operating microscope or loupes are used for improved visualization and magnification.

16.8 Tips, Pearls, and Lessons Learned

- A horizontal skin incision incorporating an existing skin crease results in the most aesthetically pleasing scar for the patient. Superficial landmarks are palpated to identify the location for the incision, which will be on the side of the pathology.
- A traditional Smith-Robinson approach is utilized to access the spine and identify the longus colli on the side of pathology.
- The longus colli is split slightly medial to the transverse tubercles above and below the level of pathology and the vertebral artery is identified.
- Depending on the level of pathology and alignment of the spine, the starting point and the angulation of drilling will vary in order to arrive at the foramen of interest.
- For upper-level pathology (C3–C4) 1 to 2 mm of the superomedial transverse process (TP) and 2 to 3 mm of the superolateral vertebral body of the caudal level is removed and the bur is directed in a cephalad direction.
- For C4–C5 or C5–C6 level pathology, 1 to 2 mm of the medial TPs of the rostral and caudal levels are drilled along with 2 to 3 mm of the lateral uncinate process directly perpendicular to the spine towards the posterior longitudinal ligament (PLL).
- For C6–C7 or C7–T1 levels, 2 mm of the medial portion of the TP, 2 to 3 mm of the inferolateral vertebra, and 2 to 3 mm of the rostral vertebra is removed. The trajectory is continued in a caudal direction.
- Curettes are used to remove disk material or bony spurs affecting the nerve root and to enlarge the foramen if necessary.
- It is important to maintain caution while drilling the uncinate process because the nerve root is located directly adjacent to it. The safest approach involves removing the thin layer of bone that remains of the uncinate process by fracture rather than drilling.
- Upturned curette or Penfield no. 4 elevator (Integra Miltex) permits palpation of TP. The TP will act as a crucial superficial landmark for the approach.
- An imaginary line formed by connecting the medial aspects of the TPs above and below the index disk level indicates the lateral border of exposure outside of which there is risk of injury to the vertebral artery (▶ Fig. 16.1). It is imperative to determine the location of the vertebral artery from preoperative imaging (▶ Fig. 16.2).
- Do not remove the longus colli lateral to the vertebral body as it increases the risk of damaging the overlying sympathetic trunk (▶ Fig. 16.3).
- A lateral to medial approach to bone resection minimizes the amount of bone removed.
- After the incision is closed, a cervical collar is not necessary in these patients.

16.9 Difficulties Encountered

- Compared to an anterior cervical diskectomy and fusion, the surgical target of an anterior cervical foraminotomy is more cephalad and lateral, requiring an adjustment in incision location and the surgical incline.
- Vertebral artery injury remains a major risk. The extent of the foraminotomy should therefore be kept to a minimum. Bone removal should begin slightly medial to the vertebral artery and proceed in a lateral-to-medial manner to expose the target pathology while reducing the risk of damage to the vertebral artery.
- Any damage to the vertebral artery should be surgically repaired via proximal and distal exposure extension if possible.
- Because the sympathetic chain runs along the lateral aspect of the longus colli, there is risk of damage via a traction injury. Complete transection of this muscle can often lead to Horner's syndrome.

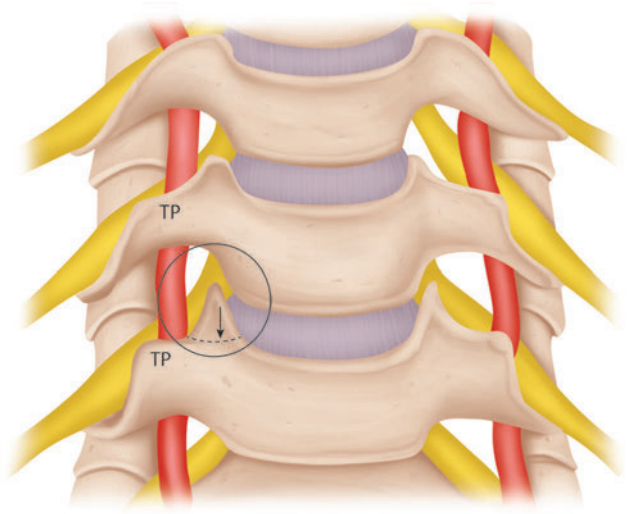

Fig. 16.1 Anterior exposure and approach for a patient with right C4–C5 foraminal stenosis. Arrow indicates the site of uncinate process takedown with 2-mm cutting bur. TP, transverse process.

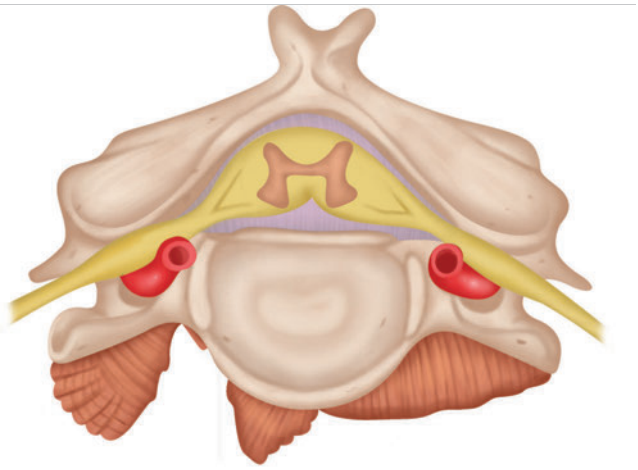

Fig. 16.2 Axial view of a vertebral body demonstrating the approach for an anterior foraminotomy. Operative approach includes drilling down through the uncinate process to the starting point of the foraminotomy. Special attention must always be paid to the nearby vertebral artery.

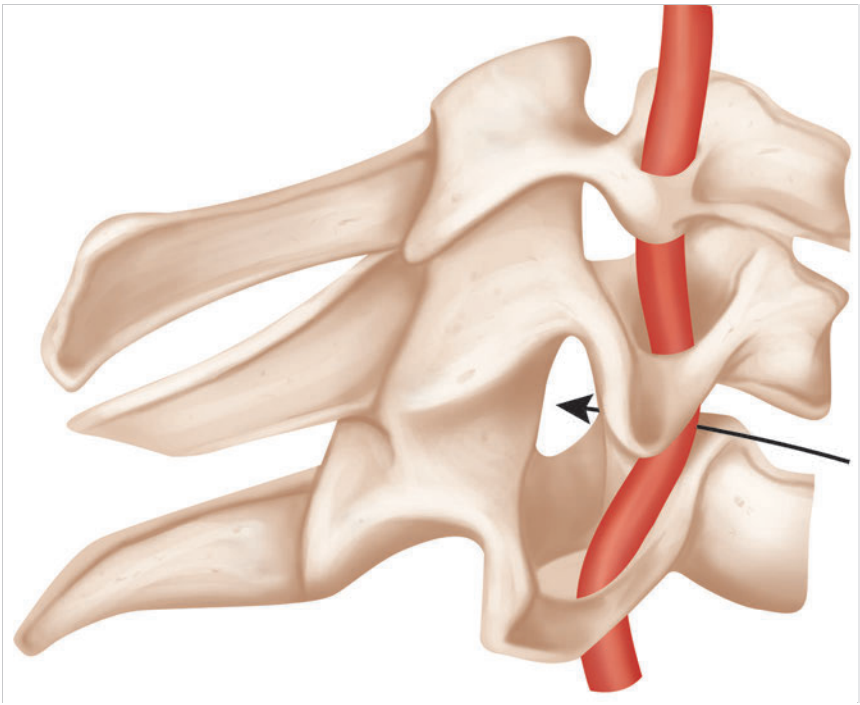

Fig. 16.3 This lateral view demonstrates the slight angle (arrow) one should take when drilling down the uncinate process.

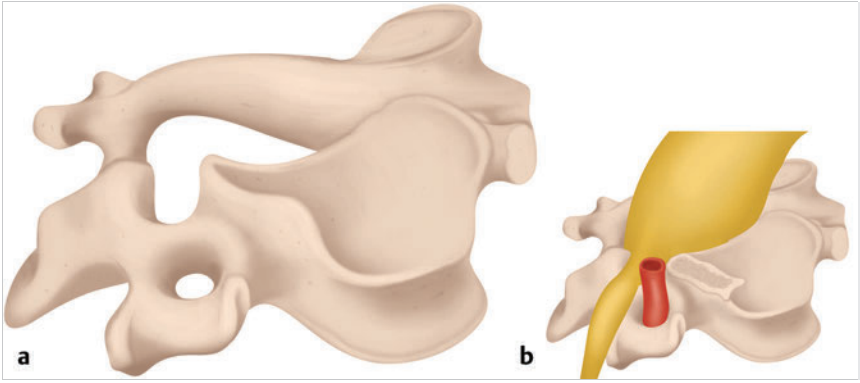

Fig. 16.4 **(a)** Oblique view of motion segment demonstrating bony anatomy. (**b**) Superimposed vertebral artery and nerve root.

- If the intervertebral disk is significantly damaged during surgery, a defect in the anulus may result in recurrent disk herniation. The foraminotomy should be made just large enough to achieve decompression, and no larger than absolutely necessary, to reduce the risk of compromising the disk.
- Because of the anatomy in this region, this procedure is difficult and carries relatively high risk. It is recommended that only very experienced or highly trained surgeons attempt this operation.

16.10 Key Procedural Steps

Always check and double check to confirm that the most symptomatic nerve root is being decompressed. Placement of the Caspar pins in the body above and below the foramen to be decompressed aids retraction and permits an ideal view of the nerve root being explored. The starting point and angle taken with the bur vary depending on the level of interest. Start the foraminotomy by first exploring the space with the upturned curette. Placing the footplate of the Kerrison along the nerve root allows decompression to be performed in a safe manner. The degree of decompression should be assessed frequently using a blunt nerve hook to ensure that only compressive bone is resected. Upon reaching the PLL, compressive pathology such as soft disk herniations or bone spurs can be excised. The PLL is often incised exposing the dura mater to check for disk fragments.

16.11 Bailout, Rescue, and Salvage Procedures

Should the patient remain symptomatic, and imaging supports further exploration, one should consider a posterior keyhole foraminotomy or a complete anterior cervical diskectomy. Performing a posterior foraminotomy ensures that the nerve is decompressed essentially circumferentially. With prior adequate anterior decompression the posterior approach should rarely be needed.

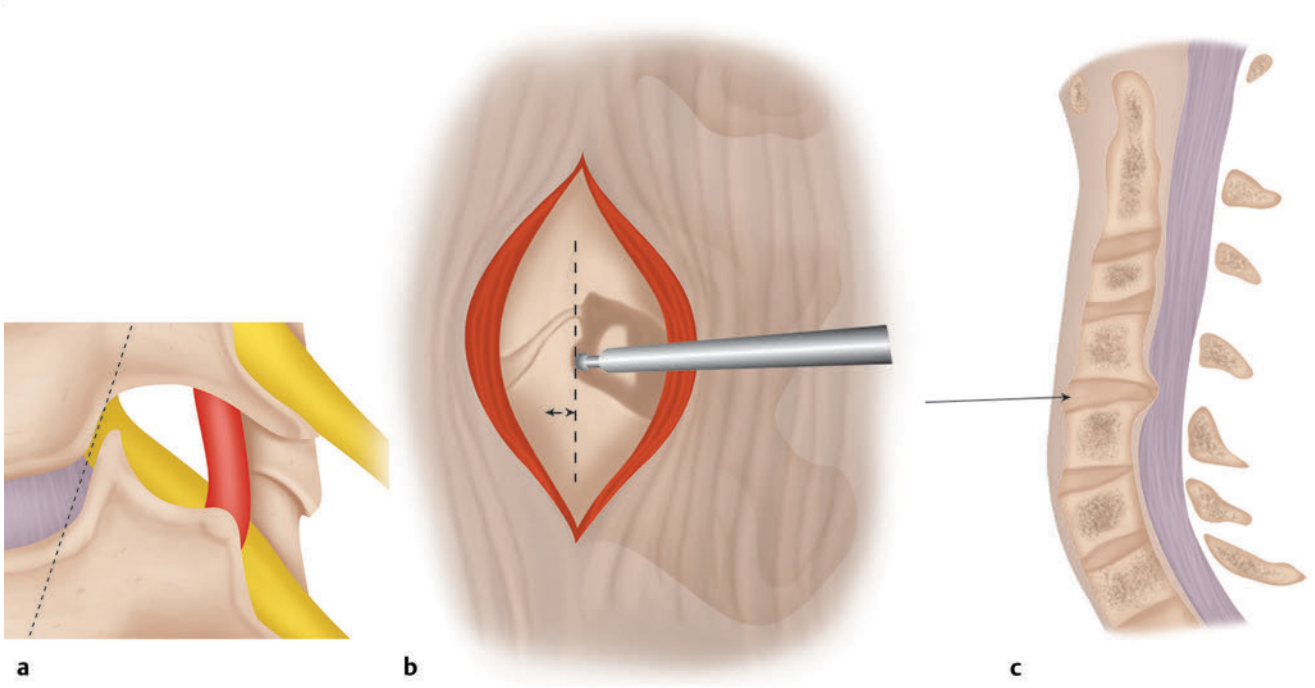

Fig. 16.5 An illustration of the left lateral transuncal approach. (**a**) A medial 2-mm portion of the transverse process cephalad and caudal is removed. The vertebral artery is disjoined laterally from the uncinate process. The lateral 2 to 3 mm of the uncinate process is drilled toward the posterior longitudinal ligament, maintaining a thin layer medially (**b**) (dotted lie) for stability. (**c**) Perpendicular surgical trajectory to target pathology from skin incision to the longitudinal axis.

Pitfalls

- Failure to address any symptomatic foraminal free disk fragments or osteophytes will result in continued symptoms of radiculopathy.
- One must understand the trajectory of the nerve root and the location of surrounding structures (e.g., pedicle, vertebral artery) to provide adequate, but safe decompression of the exiting nerve root (▶ Fig. 16.3, ▶ Fig. 16.4b, ▶ Fig. 16.5). Focal decompression of the nerve root results in a significant reduction of symptoms. Wide decompression is both unnecessary and risks injury to the surrounding structures.
- In the cervical spine, the nerve root exits above the pedicle of its like-numbered vertebra and closely hugs the inferior portion of the cephalad pedicle (▶ Fig. 16.4).
- A 2-mm cutting bur is excellent for creating a cylinder down to the PLL. The PLL can be pierced with an upturned curette and then resected with a 1–0 or 2–0 Kerrison rongeur.
- The 2-mm cutting bur can be used to drill off the lateral uncinate process. Care must be taken to not damage the medial wall of the uncinate process (▶ Fig. 16.5)
- The right-angled blunt nerve probe is excellent for exploration of the foramen.
- If a path into the foramen cannot be safely created, a temporary increase in Caspar retraction can be employed to further open the space.
- The footplate of the 2-mm Kerrison punch can be placed into the foramen for completion of the decompression.
- Always re-explore the foraminotomy cavity with the nerve hook to confirm adequate decompression.

17 Exposure of the Vertebral Artery

Brandon G. Rocque, Gregory D. Schroeder, and Daniel K. Resnick

17.1 Description

The vertebral artery runs through the foramen transversarium of the first six vertebral bodies, loops around the superolateral margin of the lamina of C1, and then enters the skull through the foramen magnum. The vertebral artery is vulnerable to injury following facet subluxation injuries, as well as during anterior cervical diskectomy (and anterior microforaminotomy), lateral mass and C3–C6 pedicle screw placement, and exposure and fixation of the craniocervical junction. Occasionally, exposure of the vertebral artery may be required (see **Video 17.1**) for direct repair or occlusion following iatrogenic injury.

Exposure of the vertebral artery from a posterior approach is relatively straightforward. Unroofing of the foramen transversarium exposes the artery safely and the soft tissue in between the transverse processes can be dissected after bony removal. This video shows exposure and planned sacrifice of the vertebral artery during the resection of a locally aggressive tumor. Balloon test occlusion had been performed pre-operatively.

17.2 Key Principles

Appreciation of the anatomy of the vertebral artery and the surrounding bony structures is essential for complication avoidance. Anatomical variation is most commonly seen at the level of C2, where 15 to 20% of patients may have aberrant vessels that preclude pars interarticularis or pedicle screw placement. Preoperative study and knowledge of alternative fixation techniques decrease the incidence of vertebral artery injury. The most important principle in managing a vertebral artery injury is to avoid a bilateral injury at all costs.

17.3 Expectations

Management of vertebral artery injuries requires immediate control of hemorrhage, the use of alternative fixation techniques, prompt assessment of cerebrovascular competence, and if necessary, repair or occlusion of the vertebral artery.

17.4 Indications

Iatrogenic injury of the vertebral artery.

17.5 Contraindications

Once hemostasis is ensured, further efforts to explore the vertebral artery are reserved for cases with demonstrated or suspected neurologic compromise.

17.6 Special Considerations

The loss of a single vertebral artery is usually well tolerated. The loss of both vertebral arteries is usually fatal. Embolism and pseudoaneurysm formation are late complications of injury that may require arterial reconstruction, bypass, or occlusion.

17.7 Special Instructions, Positioning, and Anesthesia

In the case of iatrogenic injury, the patient is positioned for the index procedure. If elective exploration is performed, the patient may be positioned supine with the head turned away from the operative site. Close monitoring of blood pressure to preserve cerebral perfusion pressure is mandatory.

17.8 Tips, Pearls, and Lessons Learned

Complication avoidance is much preferred to complication management. Careful preoperative assessment of the location of the vertebral artery in relationship to anticipated sites of operative manipulation is essential. If a vertebral artery injury is identified or suspected, the contralateral vertebral artery must be preserved. This may result in unilateral fixation (side of the injury) or the need for external immobilization. Immediate postoperative assessment of cerebrovascular anatomy and reserve should be coordinated with an experienced cerebrovascular neurosurgeon.

17.9 Difficulties Encountered

Blood loss may be rapid and significant. Depending on the site of injury, bleeding may be controlled with tamponade, packing with hemostatic agents, or simply by screw placement. Local exploration and attempts at repair may be possible in rare instances. Such attempts should not be undertaken without prior cerebrovascular experience and an adequately prepared operating room staff. Endovascular techniques for occlusion or stenting of the artery should be considered as valuable treatment options.

17.10 Key Procedural Steps

If exploration of the artery is undertaken, the surgeon must be prepared to deal with the risk of significant bleeding, hemodynamic lability, and the risk of embolization.

17.11 Bailout, Rescue, and Salvage Procedures

Injuries to the vertebral artery at or above C2 usually are encountered during the initial exposure (injuring the vessel along the rostral border of the C1 lamina) or by inadvertent laceration of the artery by a drill, tap, or screw. If the vessel is injured during the initial exposure, the site of injury is obvious

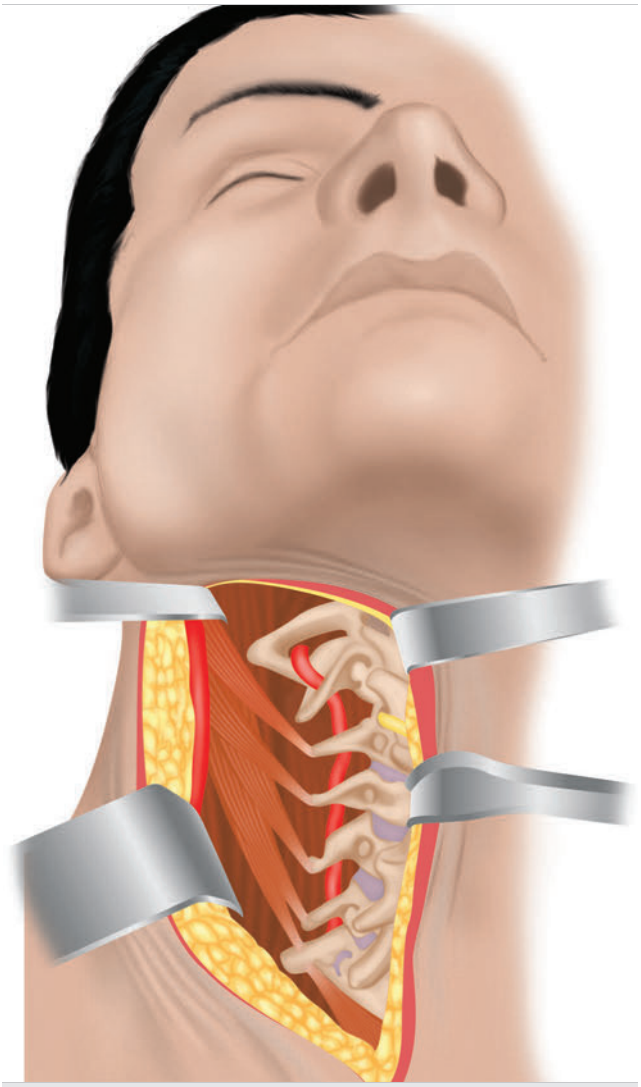

Fig. 17.1 Anterior approach to the vertebral artery through an extended anterior cervical exposure and elevation of the longus colli.

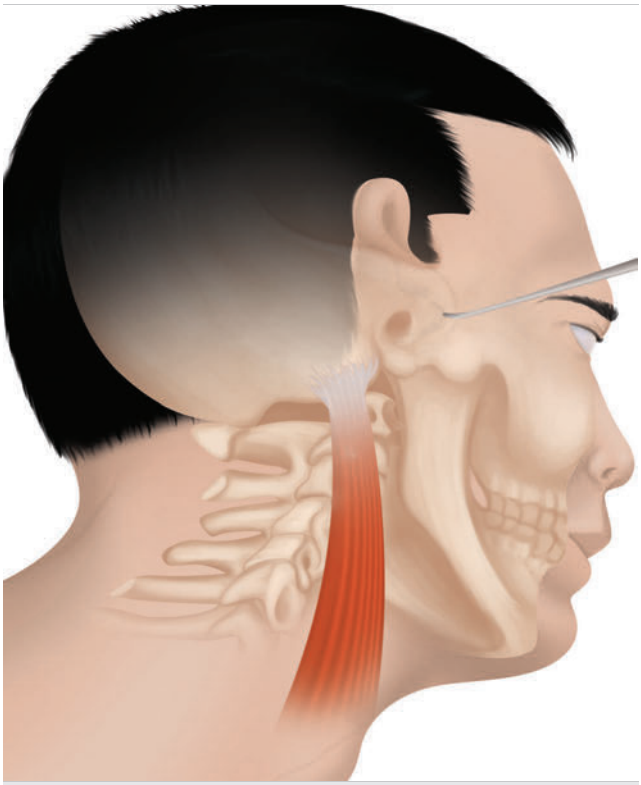

Fig. 17.2 Orientation for the lateral approach to the vertebral artery.

and direct tamponade followed by local dissection will expose the area of injury. If the bleeding is through a hole in the bone, screw placement will generally achieve hemostasis. If the injury occurs during a posterior fixation procedure below C2, injury is likely related to screw placement. Hemostasis should be obtained with screw placement; the ipsilateral construct is rapidly completed, and the contralateral vertebral artery is preserved. Postoperative imaging is obtained. Conventional angiographic study is preferred, as the visualization of the artery is unaffected by metallic artifact, and therapeutic maneuvers such as stenting or occlusion may be performed contemporaneously. If the artery is occluded, anticoagulation or bypass should be considered in cooperation with a cerebrovascular specialist. In the asymptomatic patient, no therapy may be required. Revascularization options may also include endovascular techniques and bypass procedures such as an occipital artery–posterior inferior cerebellar artery bypass.

If an injury occurs during an anterior procedure, such as during an anterior cervical diskectomy or an anterior microforaminotomy, then exploration may be feasible. Exploration may be considered when hemostasis cannot be adequately obtained locally, or when immediate preservation of the artery is deemed to be essential (dominant vertebral artery, known contralateral occlusion) and the surgeon has some experience with vascular repair.

The vertebral artery may be exposed over several segments from an anterolateral approach. It may be accomplished through an extension of the standard anterior cervical approach. The incision is made along the border of the sternocleidomastoid, and may be extended to just posterior to the mastoid process. The precervical fascia is divided and the plane medial to the sternocleidomastoid is exploited to expose the prevertebral fascia overlying the spine. The longus colli is mobilized to expose the transverse processes (▶ Fig. 17.1) and the transverse foramina are opened using a drill or Kerrison rongeurs. For more rostral exposure of the vertebral artery, a more lateral approach is preferred (▶ Fig. 17.2). The sternocleidomastoid muscle is detached from the mastoid process and reflected caudally (leave a cuff of muscle attached to the mastoid for later closure). Identification and preservation of the spinal accessory nerve will avoid a postoperative shoulder drop (▶ Fig. 17.3). As the sternocleidomastoid muscle is retracted, the transverse processes of the upper three or four vertebral bodies will be palpable, as will the pulsatile vertebral artery. Serial section of the splenius capitis and levator scapula muscles will expose the lateral aspect of the vertebral artery as it runs in the transverse foramen and then loops across C1 (▶ Fig. 17.4).

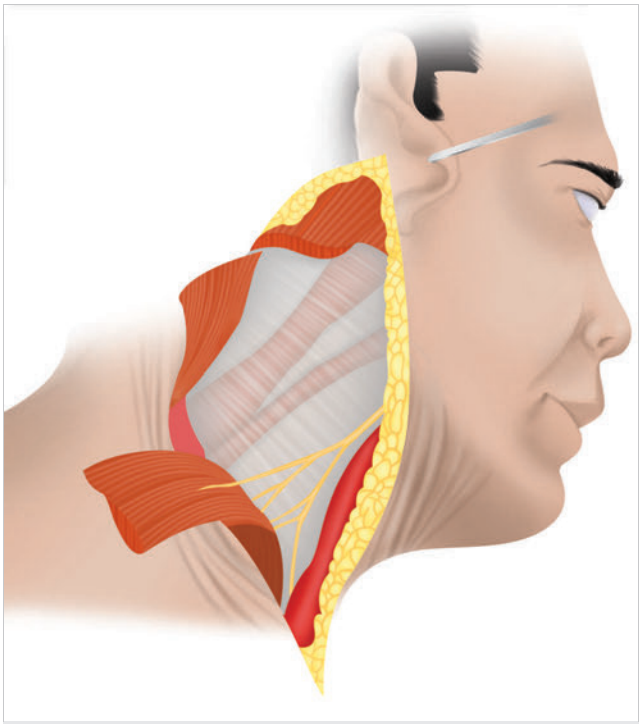

Fig. 17.3 Reflection of the sternocleidomastoid muscle with preservation of the spinal accessory nerve.

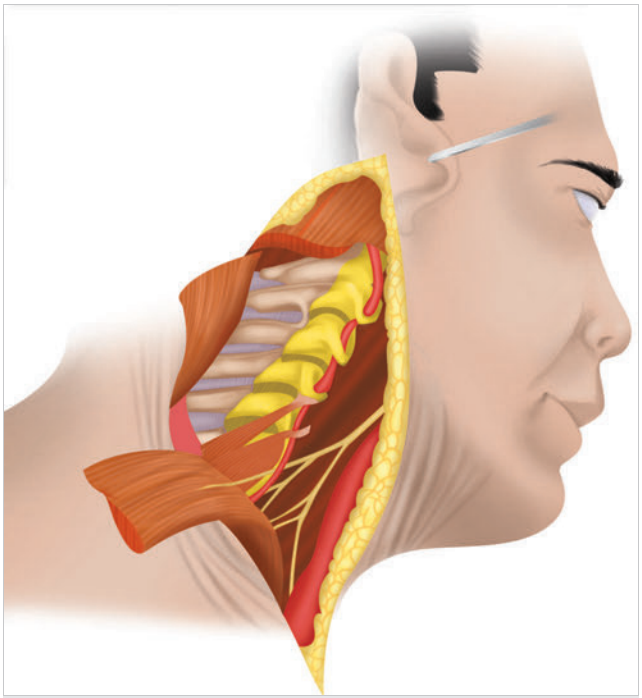

Fig. 17.4 The vertebral artery is exposed as it runs around the lateral mass of C1 and may be exposed further caudally by opening the foramen transversarium of the caudal vertebral bodies.

Pitfalls

- In cervical spine surgery, exposure of the vertebral artery is only required if there is an iatrogenic injury. A surgeon should never begin a cervical case without a critical understanding of the location of the vertebral artery.
- Many patients are asymptomatic after a unilateral vertebral artery injury, but a bilateral injury always has potentially devastating consequences. Once the bleeding has been controlled, do not continue with any part of the surgery that may put the contralateral artery at risk; often this means that unilateral fixation is used.
- Once a vertebral artery injury occurs, communication with the anesthesiologist, nursing staff, and preferably a vascular surgeon is critical. Failure to communicate with the rest of the medical staff about the severity of the problem may lead to a delay in the ideal treatment.

18 Anterior Cervical Corpectomy

James C. Farmer

18.1 Description

Anterior cervical corpectomy is a method of decompressing the cervical spinal cord and nerve roots. It is performed by removing the disk above and below the vertebral body that is to be resected, followed by the vertebral body itself (complete corpectomy) (▶ Fig. 18.1). Under some circumstances, only one disk is removed along with a portion of the adjacent vertebral body/bodies (partial corpectomy).

18.2 Key Principles

Large osteophytes with spinal cord compression extending behind the intervertebral disk space, ossification of the posterior longitudinal ligament (PLL), as well as disk herniations positioned behind the vertebral body can be resected utilizing this surgical technique. Excellent decompression of the spinal cord and nerve roots can be achieved. Sagittal deformities such as kyphosis either pre-existing or postsurgical (postlaminectomy) can be corrected through this technique.

18.3 Expectations

Following a corpectomy, all anterior compression of the spinal cord and nerve roots should be relieved. If kyphosis exists preoperatively, it can be corrected allowing restoration of normal cervical lordosis. On occasion, supplemental posterior stabilization may be required depending on the number of segments decompressed, history of prior posterior cervical decompression, and the overall bone quality.

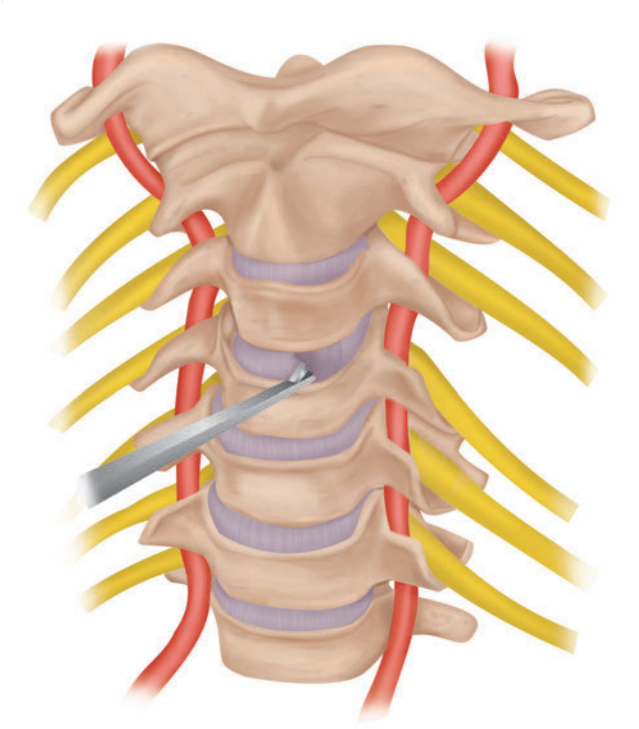

Fig. 18.1 Anterior diskectomy.

18.4 Indications

- Cervical spondylotic myelopathy
- Pre-existing cervical kyphosis with spinal cord or nerve root compression
- Vertebral burst or compression fractures
- Vertebral body neoplasms
- Cervical diskitis or osteomyelitis
- Cervical disk herniations with fragments migrated behind the vertebral body

18.5 Contraindications

- Previous radiation to the anterior neck
- Aberrant vertebral artery anatomy
- Severe chin on chest deformity that is rigid, making the anterior approach impossible
- Medical contraindications to a general anesthetic

18.6 Special Considerations

Plain radiographs are useful in evaluating overall sagittal alignment, flexibility of deformities, dynamic instability, as well as the presence of OPLL and osteophytes.

Magnetic resonance imaging (MRI) remains the modality of choice when treating patients with cervical disorders; MRI with flexion and extension sagittal images can be helpful in evaluating positional effects on cervical stenosis as well as evaluating the reduction of instability. Computed tomography (CT), which can be combined with myelography, provides the best imaging of bony structures. Myelography also allows dynamic visualization of changes to the spinal cord and nerve roots in various positions of the neck. A CT scan is paramount when evaluating ossification of the PLL to adequately assess the degree of ossification as well as the number of levels involved. It also better evaluates the degree of foraminal stenosis from bony osteophytes.

18.7 Special Instructions, Positioning, and Anesthesia

The patient is positioned supine with arms at the side and carefully padded and protected. A roll is placed between the shoulders to allow the head to be positioned in a neutral to a slightly extended position. It is important to avoid overextension of the neck as this can cause spinal cord impingement and possible injury. Gardner-Wells tong traction can be used. Spinal cord monitoring is recommended. In patients with significant

spinal cord compression or instability, fiberoptic intubation may be necessary. Prior to surgery, fluoroscopic imaging allows the overall sagittal alignment to be visualized and adjusted. Adequate visualization of the distal surgical level can be determined and pull on the shoulders subsequently adjusted.

18.8 Tips, Pearls, and Lessons Learned

Obtaining proper imaging studies as well as a careful preoperative evaluation of these studies is paramount for optimal surgical treatment. Determination of the number of levels involved as well as the extent of compression at each individual level is essential. Additionally, careful evaluation of the location and course of the vertebral artery is necessary to avoid iatrogenic injury. If there is any question, a CT angiogram can be obtained to precisely determine the vertebral arteries course. At the time of surgery, complete diskectomies prior to resection of the vertebral bodies facilitate assessment of the depth of the vertebral body as well as the location of the spinal canal. In cases of ossification of the PLL where the ossification is extremely adherent to the dura, direct resection can be dangerous. Successful decompression can be performed by removing the PLL on either side of the ossified area, and allowing it to float away anteriorly from the cord (anterior floating technique) without necessitating direct resection and high risk of dural tear and subsequent spinal fluid leak. When performing the corpectomy, a high-speed bur can be used to resect most of the vertebral body, leaving only a thin rim of posterior cortical bone. The posterior cortical bone can be removed using either a small curette or a Kerrison rongeur. An operating room microscope aids in the decompression.

18.9 Difficulties Encountered

It is imperative to identify the uncovertebral joints bilaterally when performing the decompression. This enables the surgeon to maintain orientation to the midline, facilitating an adequate decompression of the spinal canal, and avoiding dissecting too laterally with the risk of injury to the vertebral artery. Careful resection of the posterior cortex and PLL is necessary to avoid injury to the dural sac and spinal cord. Significant bleeding can occur during resection of the vertebral body and can make visualization difficult at times. This can be controlled with the judicious use of bone wax and hemostatic agents such as Gelfoam (Pfizer Pharmaceuticals), SURGICEL (Johnson & Johnson), and Avitene (CR Bard). Bone wax should be utilized only after sufficient local bone graft has been obtained from the vertebral bony resection.

18.10 Key Procedural Steps

During the performance of multilevel corpectomies, adequate surgical exposure is paramount. During surgical exposure, the raising of subplatysmal flaps as well as the takedown of fascial structures along the surgical interval provide optimal exposure and enable mobilization of the soft tissue structures along the anterior spine. Often, a transverse incision can be utilized,

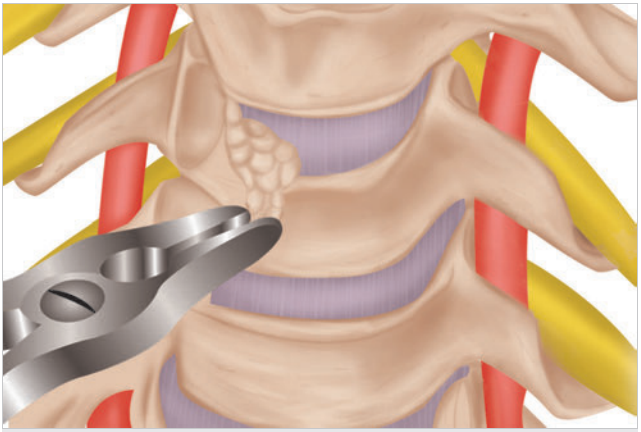

Fig. 18.2 The corpectomy can be initiated with 3-mm Leksell rongeurs to two-thirds depth of the vertebral body.

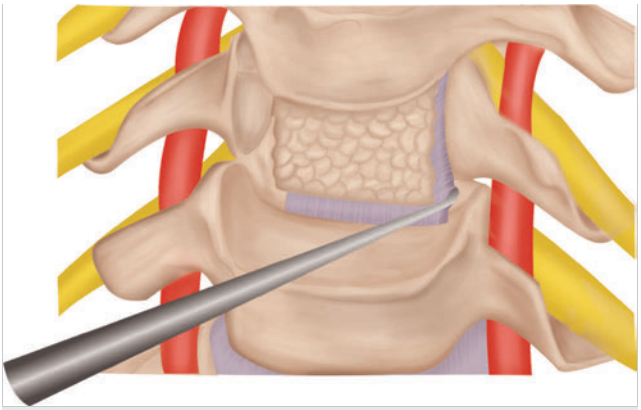

Fig. 18.3 Thinned posterior cortex can be removed with a forward-angled curette.

which can be curved upward and downward at the extreme medial and lateral edges as needed. The operating room microscope provides optimal illumination and excellent visualization of the surgical field for both the surgeon and the assistant. Loupe magnification and a headlight also enable safe neural decompression. Standard diskectomies should be performed above and below the vertebral body to be resected. Visualization of the PLL and uncovertebral joints on each side is necessary for an adequate decompression. The initial portions of the corpectomy can then be performed either with a rongeur or with various high-speed burs (▶ Fig. 18.2). The width of the decompression should be on average 15 to 16 mm. Again, identification of the uncovertebral joints during the decompression facilitates assessment of the widest extent of decompression that can be performed should it be needed. The PLL does not routinely need to be excised unless it is felt that a compressive lesion posterior to the PLL exists or in the case of an ossification of the PLL. With ossification of the PLL, the surgeon may elect to remove the entire ossified ligament, or in cases where it is felt to be exceedingly adherent to the dura, the anterior floating method can be utilized (▶ Fig. 18.3).

Once the decompression is completed, the end plate should be prepared and burred down to underlying bleeding cancellous bone. Maintaining a small posterior lip along vertebral

bodies helps prevent graft extrusion in the canal. The graft should be carefully placed and then traction removed to assess the fit and stability of the graft. Grafting options include a tricortical iliac crest bone graft, autograft fibula, allograft fibula, and interbody cages with cancellous bone graft. Sufficient local bone graft can often be obtained and used in combination with an interbody cage avoiding the need to harvest autologous bone graft from other sites. If an anterior plate is to be used, it is important to remove the distractive forces across the head and neck prior to placement of the plate. Screws should not be placed into the graft, as this may cause the graft to break. Prior to placement of the graft, the neural foramina should be assessed, and, should it be necessary, foraminotomies performed with a Kerrison rongeur.

18.11 Bailout, Rescue, and Salvage Procedures

In the case of graft extrusion or hardware failure, an urgent revision anterior procedure should be performed with revision of the plate and graft, and likely a subsequent posterior stabilization procedure. In the case of a dural tear with spinal fluid leak, options include a primary repair or use substances such as fibrin glue or DuraGen (Integra Life Sciences) and DuraSeal (Covidien). Primary repair can be difficult due to the small size of the working space. In cases where it is felt that there will be a high likelihood of a persistent spinal fluid leak, a lumbar drain may be necessary. In the case of a vertebral artery injury, options include local control with the use of hemostatic agents, a direct repair of the vessel, placement of a stent to bypass the injury, or ligation of the injured vessel. Intraoperative consultation with a vascular surgeon may be helpful.

Pitfalls

- Iatrogenic injury to the vertebral artery can occur due to either an aberrant vertebral artery or to excessive lateral decompression.
- Dural tear with a subsequent spinal fluid leak and neurologic injury can occur during resection of the posterior vertebral body and PLL.
- Graft extrusion and hardware failure can occur in cases of prior posterior decompression procedures, in multilevel corpectomies, or in cases of poor quality bone. A posterior stabilizing procedure with instrumentation may be necessary to adequately protect the anterior construct.

19 Anterior Open Reduction Technique for Unilateral and Bilateral Facet Dislocations

G. Alexander Jones, Ghaith Habboub, and Edward C. Benzel

19.1 Description

Unilateral or bilateral cervical facet dislocations may be reduced during an anterior fusion and fixation procedure. If successful, open reduction may eliminate the need for a staged anterior and posterior procedure.

19.2 Key Principles

- Several techniques exist for anterior reduction of cervical facet dislocations, all of which are based on a standard anterior cervical approach.
- These techniques often eliminate the need for traction, closed manual reduction, or a posterior approach.
- In all cases, the posterior longitudinal ligament and intervertebral disk must be resected prior to reduction.
- Fixation and fusion are carried out after reduction.

19.3 Expectations

A successful anterior open reduction allows for indirect spinal cord decompression and obviates the need for a staged posterior approach.

19.4 Indications

An anterior open reduction is an option as a primary means of reducing cervical facet dislocation. It may also be used in the event that cervical traction is unsuccessful in restoring alignment.

19.5 Contraindications

If there is a posterior hematoma or dorsal compression that may need to be decompressed, it is safer to proceed with a posterior decompression and open reduction rather than an initial anterior open reduction. In the case of a severely comminuted facet fracture, an open ventral reduction is less likely to be successful.

19.6 Special Considerations

- Awake, fiberoptic intubation should be considered to minimize the risk of neurologic injury.
- Neurophysiological monitoring, including motor-evoked potentials, will allow direct monitoring of spinal cord function during the procedure.
- Creation of a temporary, focal kyphosis is generally required to disengage the facet joints for reduction. Sagittal angulation should be restored prior to placement of graft and instrumentation.

19.7 Special Instructions, Positioning, and Anesthesia

In some cases, the dislocation may prove difficult, if not impossible, to reduce, thus requiring an additional posterior approach. Radiographic confirmation of the reduction should be obtained prior to placement of a bone graft and plate. This may be accomplished with intraoperative plain radiographs or fluoroscopy.

Patients who are not already intubated upon arrival in the operating room should be submitted to an awake fiberoptic intubation to minimize the risk of further neurologic injury. Distraction of the interspace can be accomplished in a controlled manner during the operative procedure. This obviates the need for traction.

19.8 Tips, Pearls, and Lessons Learned

Several techniques may be used for reduction. Caspar distraction pins may be inserted into the vertebral bodies, with the shafts positioned at a divergent angle of 10 to 20 degrees (▶ Fig. 19.1). Bringing the pins into a parallel orientation and placing them in the distracter, followed by controlled distraction, often results in disengagement of the facets, by creating a temporary, focal kyphosis (▶ Fig. 19.2). The rostral level is then

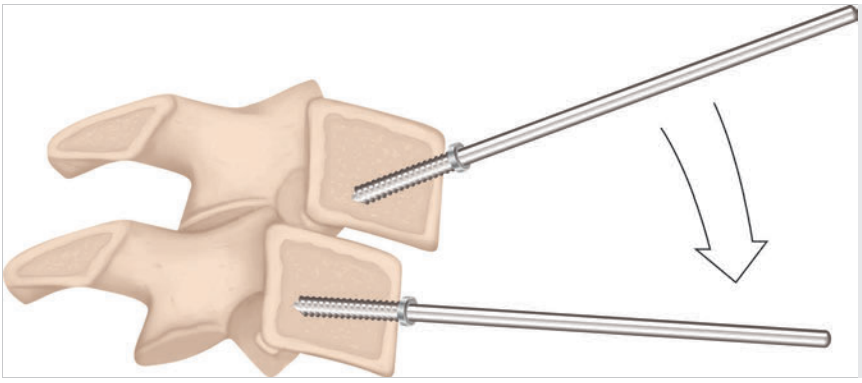

Fig. 19.1 Placing distraction pins at a 10- to 20-degree angle with respect to each other in the sagittal plane permits the creation of a kyphosis to disengage the facets.

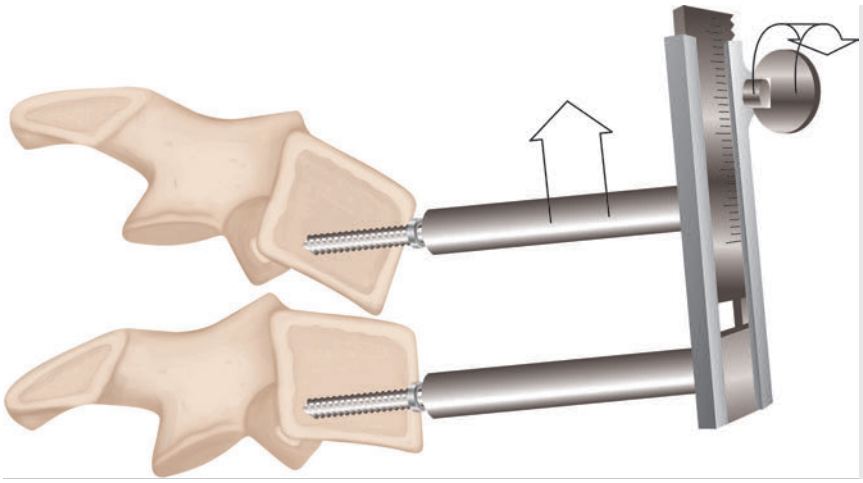

Fig. 19.2 Slight distraction can also be used to cause the facets to disengage. Dorsal force application to the rostral vertebra assists in reduction of the dislocation.

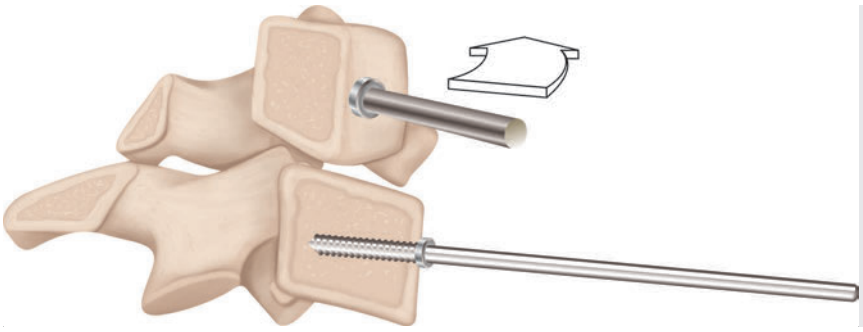

Fig. 19.3 Placing the pins at a 15-degree angle with respect to each other in the coronal plane allows reduction of a rotational deformity when distraction is applied.

translated dorsally, occasionally with the application of moderate pressure to restore alignment.

In place of the distracter, the pin drivers used for pin application may be left on the pins. This facilitates additional freedom of movement in the coronal plane. Placing a solid object, such as a small bone tamp, between the vertebral bodies ventrally in the interbody space provides a solid fulcrum on which the bending moment may be applied. If osteopenia is a concern, longer pins may be placed with bicortical purchase.

Sagittal angulation should be corrected prior to placement of a bone graft and instrumentation. This may require removal and repositioning of one or both distraction pins.

In the case of a unilateral dislocation, the distraction pins should be applied with a divergent angle in the coronal plane to allow the rotational deformity to be reduced after distraction (▶ Fig. 19.3).

Alternatively, a small curette may be inserted in the interspace and braced against the cephalad end plate of the caudal vertebral body. The handle is rotated rostrally while the tip remains stationary. As the motion is begun, the predominance of the resultant force is that of distraction, but as the curette gains a greater angle relative to the end plate, it forces the rostral vertebral body dorsally (▶ Fig. 19.4).

Another option involves the use of a vertebral body spreader. Distraction across the disk space is applied first, and then the spreader is rotated in a rostral direction to restore alignment along with a rotational maneuver in the setting of a unilateral facet dislocation (▶ Fig. 19.5).

19.9 Difficulties Encountered

The dislocation may prove to be difficult to reduce. Therefore, be prepared to perform a posterior procedure if necessary. Many techniques have been described where an undersized graft is placed or an anterior cervical plate is fixated only to the cephalad vertebrae along with a graft that allows the graft to maintain its alignment with the vertebral bodies following the posterior reduction.

19.10 Key Procedural Steps

A standard anterior cervical diskectomy and fusion (ACDF) approach is used. The importance of a complete, aggressive diskectomy prior to reduction cannot be overemphasized. The posterior longitudinal ligament should be resected across its entire width to facilitate manipulation of the vertebral bodies. Once these steps are complete, the dislocation may be reduced, foraminotomies performed if needed, a bone graft placed, and a plate applied.

19.11 Bailout, Rescue, and Salvage Procedures

If there is a sagittal plane deformity (kyphosis) at the injured level, the caudal portion of the rostral body may be resected with a high-speed drill to allow access to the disk space (▶ Fig. 19.6).

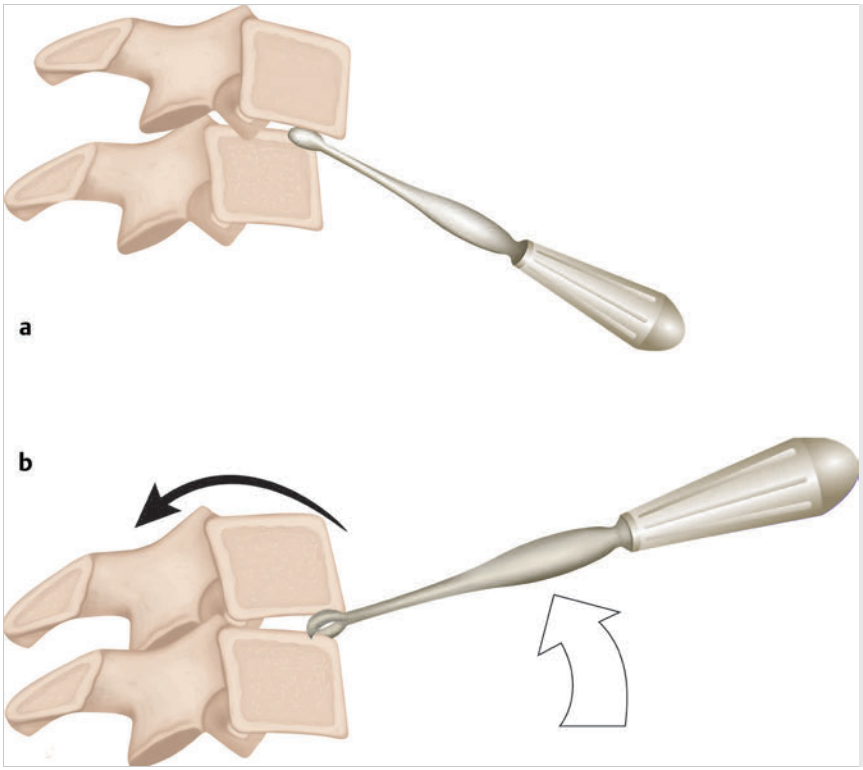

Fig. 19.4 **(a)** A curette (or similar device) can be used to create distraction, followed by (**b**) dorsal translation of the rostral vertebra, to reduce the deformity.

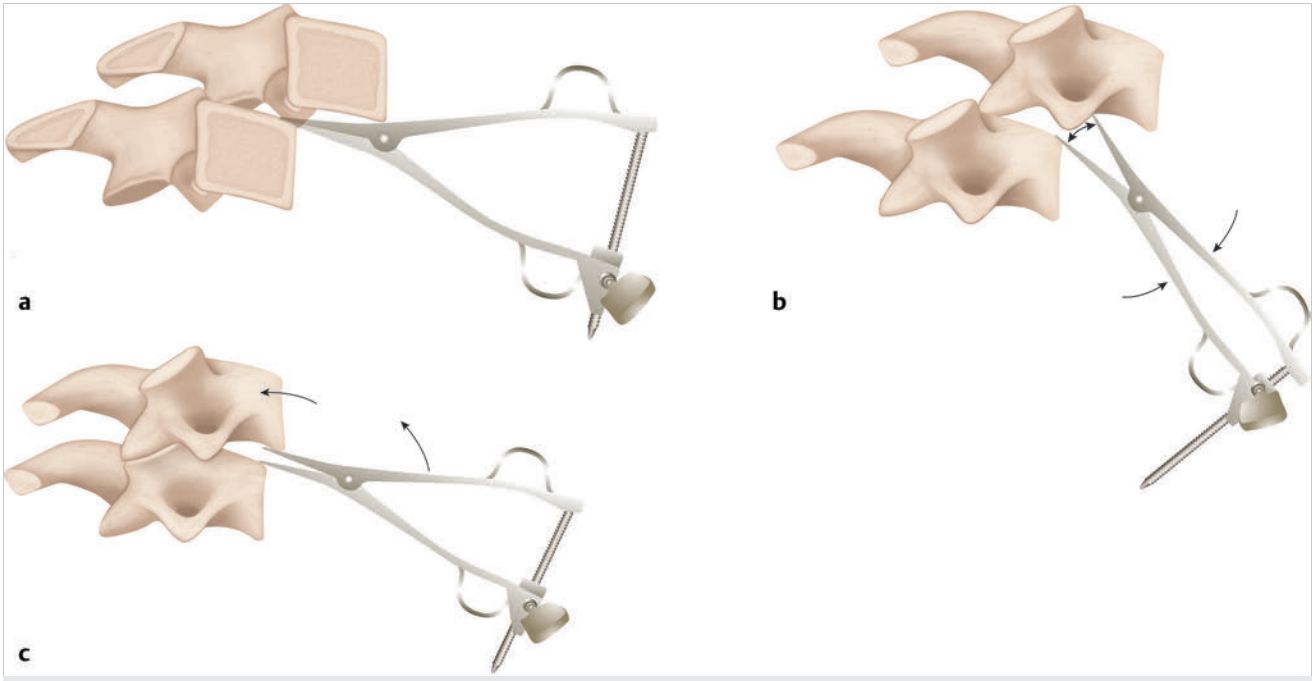

Fig. 19.5 **(a)** A disk interspace spreader can be used to reduce deformities by placing the spreader in the disk interspace at an angle. (**b**) Distraction is then applied to disengage the facet joints, followed by rotation **(c)** to reduce the deformity.

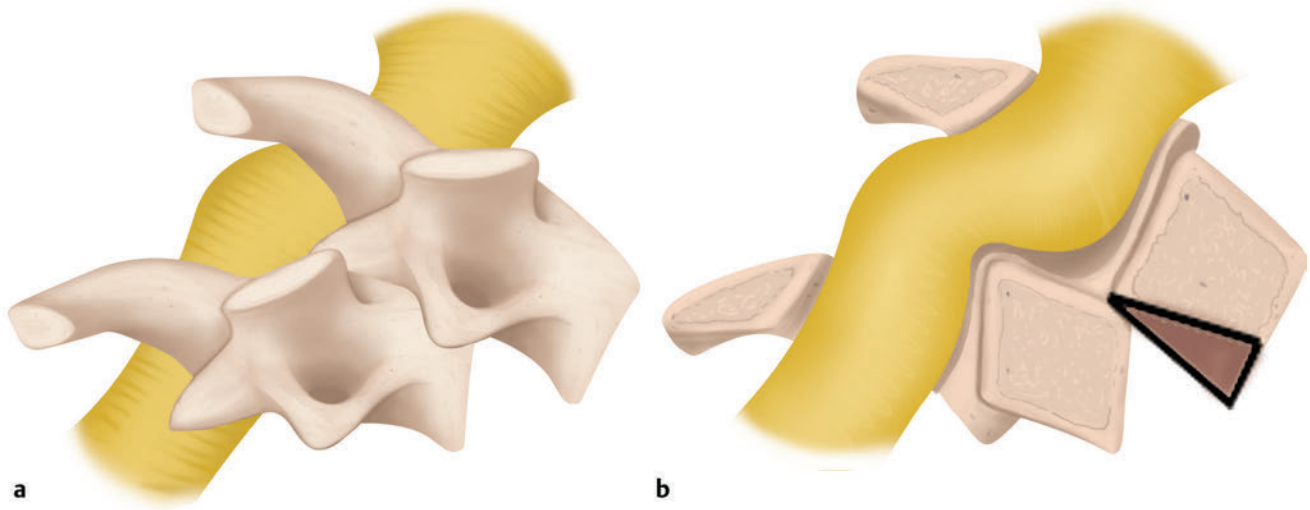

Fig. 19.6 (a, b) A dislocation may necessitate the removal of a portion of the ventrocaudal aspect of the rostral vertebral body (shaded area) to visualize the disk interspace, and allow the translation required for reduction of the dislocation.

Pitfalls

- Overdistraction during the reduction process may result in neurologic injury. Due to the resultant instability, an anterior plate should always be used.
- Failure to resect the intervertebral disk or posterior longitudinal ligament prior to reduction could cause a fragment of bone or disk to impact the spinal cord during reduction, with resultant neurologic worsening.

Section IV

Anterior Cervical Arthrodesis and Instrumentation

IV

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20 Odontoid Screw Placement

Darrel S. Brodke, Prokopis Annis, and Brandon D. Lawrence

20.1 Description

This procedure provides for the reduction and fixation of a type II or high type III odontoid fracture with a precisely placed lag/compression screw.

20.2 Key Principles

Anatomical alignment at the fracture site by initial positioning or intraoperative reduction is vital to the success of this procedure. The lag screw must be able to glide through the vertebral body and firmly purchase the odontoid fragment to gain firm compression at the fracture edges. This requires that the threads traverse and purchase the tip of the odontoid in a bicortical fashion.

20.3 Expectations

Screw fixation of the odontoid fracture should significantly improve fracture-healing rates over those treated in halo-vest immobilization, and avoid the limitations of a primary C1–C2 fusion with associated loss of motion.

20.4 Indications

Patients with acute or subacute (less than 6 months old) type II or high type III odontoid fractures, particularly those at higher risk of pseudarthrosis, are ideal for this technique.

20.5 Contraindications

- Fractures older than 6 months
- Reverse (anterior) oblique fracture line, angling from posterior or rostral to anterior caudal (▶ Fig. 20.1)

Fig. 20.1 A reverse (anterior) oblique fracture, not amenable to odontoid screw fixation

- Significant osteoporosis or fracture comminution
- Inability to gain anatomical reduction
- Inability to gain appropriate screw placement due to body habitus (barrel chest) or associated disease process (ankylosing spondylitis)

20.6 Special Considerations

Patients older than 50 years of age, with fractures displaced greater than 4 to 5 mm, have the highest rate of nonunion with halo fixation. They should be considered for immediate odontoid screw fixation. Likewise, younger patients with high-risk lifestyles and elderly patients who may poorly tolerate 3 months in a halo vest may be considered for immediate fixation. Those patients who do undergo 3 months in a halo and have persistent motion at the fracture site may still heal with screw fixation. Although there is often some loss of motion following odontoid fracture treatment by any means, the motion remains better than with C1–C2 fusion, which is associated with a 50% loss of rotation of the neck. If considering odontoid fixation in the elderly (as opposed to a posterior fusion), two screws should be used, as this has been shown to significantly increase stability.

20.7 Special Instructions, Positioning, and Anesthesia

The patient should be positioned supine on the operating table with the head in traction. This can be accomplished with the Mayfield three-pin head holder, Gardner-Wells tongs, and a pad under the head and between the shoulder blades, or with halter traction. The arms may be gently taped down to the sides with mild traction, though the shoulders rarely block visualization. If the endotracheal tube can be positioned off to the side in the mouth, this will allow improved visualization of the odontoid in the anteroposterior (AP) plane.

20.8 Tips, Pearls, and Lessons Learned

- Get as close to anatomical reduction as possible prior to the prep and drape. This can be accomplished by adjusting the height of the head on towels or foam, or by placing towels under the shoulder blades. Both rotation of the neck and forward translation of the head, as compared with the chest, may be required to reduce the fracture and allow access for screw placement.
- Use biplane fluoroscopy to obtain quick AP and lateral views of the odontoid throughout the procedure (▶ Fig. 20.2). A bite block, wad of gauze, or a wine cork with cutouts for the teeth may be used to hold open the mouth, improving AP visualization of the odontoid tip.

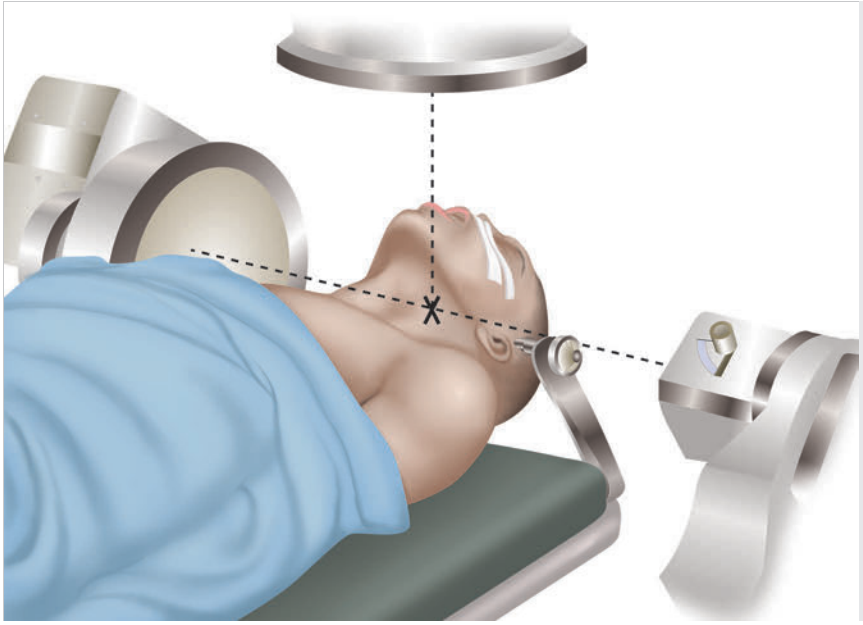

Fig. 20.2 Intraoperative positioning with biplane fluoroscopy.

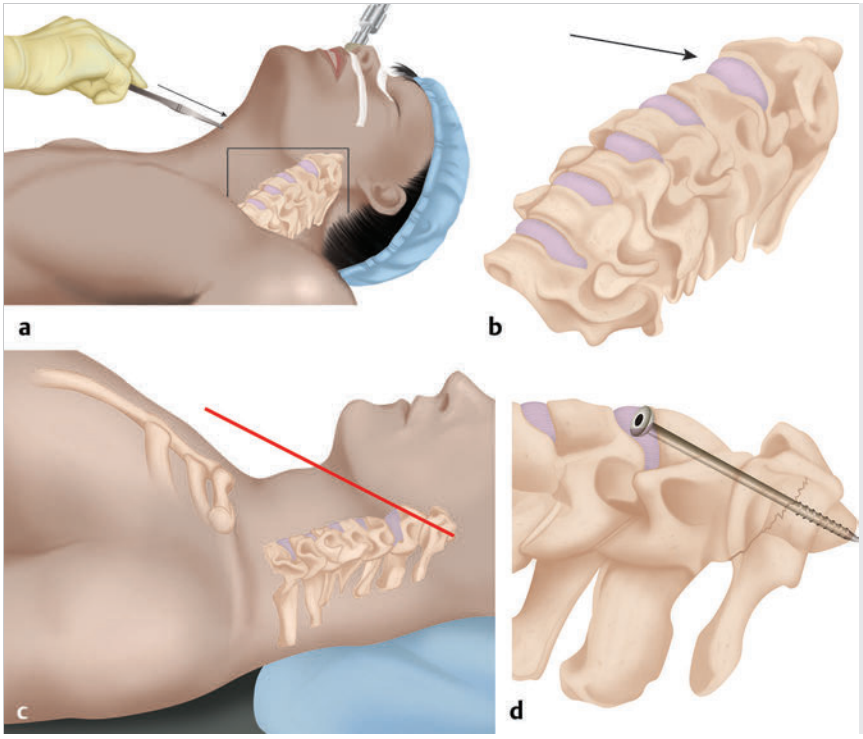

Fig. 20.3 (a–d) Odontoid screw placement requires neck extension and occasionally some forward translation of the head, so that the screw trajectory is anterior to the chest wall.

- Ensure access to the screw trajectory above the chest wall, and confirm on the lateral fluoroscopy view prior to prep and drape (▶ Fig. 20.3).
- Approach through a C5–C6 level skin incision (on the right for a right-handed surgeon). Have the endotracheal tube taped off to the left side to keep out of the way.
- Enter the C2 body at the C2–C3 disk, under the anterior edge of the body. This may require removing a small amount of the C3 body anteriorly, as well as some of the C2–C3 disk anulus, to get the correct trajectory.
- If two screws are planned, start with the far side (left side for a right-sided approach) and make sure that there is adequate room for the heads of both screws.
- Further reduction may be achieved by using a radiolucent retractor that also enables the assistant to place anterior to posterior pressure on either the C2 vertebral body or the odontoid fragment by placing the retractor just beneath the anterior aspect of the C1 ring.
- Using a cannulated system exposes some risk, as the small diameter guidewire required often deflects around

cortications as it is passed up the odontoid and then binds when the drill passes. This causes the guidewire to dangerously advance out the tip of the odontoid. More control of direction/path is achieved using a noncannulated drill, and the guidewire is not necessary for screw placement.

20.9 Difficulties Encountered

Patient body habitus or position may inhibit access to the proper trajectory for screw placement. If the chest is barrel shaped, the drill will not be able to get low enough. If the neck has a fixed flexed position, the proper screw placement is also blocked. Fracture pattern may inhibit screw fixation. If the fracture has a reverse oblique orientation, angling from posterior rostral to anterior caudal (▶ Fig. 20.1), attempts at fracture compression will cause loss of reduction. Inability to obtain fracture site compression will lead to a higher rate of failure. Additional difficulties may be encountered if there is poor fluoroscopic visualization. Taking the time to ensure good AP and lateral fluoroscopic views before beginning the procedure is a key element to success.

20.10 Key Procedural Steps

Following intubation and placement of cranial traction, two C-arms are positioned for perfect, simultaneous AP and lateral views of the odontoid (see **Video 20.1**). The head and neck are then positioned for anatomical alignment of the fracture. This may require both rotation and translation of the head, usually with some flexion and some anterior translation. The screw trajectory is then checked on the lateral view with a Kirschner wire (K-wire) laid alongside the neck, to ensure that the sternum is clear of the path for instruments and the screw can be placed appropriately. The neck is prepped for a right-sided anterior approach at the C5–C6 level.

A standard anterior approach to the cervical spine is performed, between the midline structures and the carotid sheath. Once down between the longus colli muscles, blunt dissection is continued up to the C2 vertebral body, and a radiolucent retractor is used to allow an AP fluoroscopic view. The C3 vertebral body is notched and the anterior anulus of the C2–C3 disk is removed in midline. A drill is advanced through the undersurface of the anteroinferior corner of the C2 body.

Under AP fluoroscopic control, the drill is advanced up through the C2 body, aiming for the midpoint of the odontoid tip. The lateral view is used to confirm a trajectory aimed up through the midportion of the odontoid to its tip. The drill is advanced to the fracture site. If the fracture is well reduced, the drill is advanced across the fracture site, into the proximal fragment, then slowly and carefully through the tip of the odontoid without further advancement, feeling the change in bone density as the cortex is met and then penetrated. If reduction is required, this is performed before advancing the drill.

A decision is now made to place either a partially threaded or a fully threaded screw. The partially threaded screw is a natural lag screw, allowing compression at the fracture site. A fully threaded screw requires overdrilling of the body fragment to become a lag screw and allow compression. If a partially threaded screw is to be used, the length is measured off of a depth gauge or the drill. The odontoid fragment is tapped all the way to the cortical bone at the tip and the screw is placed, gaining purchase in the cortical tip.

If a fully threaded screw is to be used, the C2 body is overdrilled with a drill the same size as the outer diameter of the screw and advanced up to the fracture site. The odontoid fragment is then tapped and the screw advanced up through the tip of the odontoid, again obtaining purchase in the second cortex. As the screw is then advanced, the head of the screw contacts the base of C2, the tip achieves purchase on the proximal fragment, pulling it distally, and the fracture edges are compressed.

20.11 Bailout, Rescue, and Salvage Procedures

During initial setup and fracture reduction, increasing or decreasing the amount of traction may help. Just before drilling the odontoid fragment, further reduction can be obtained with help from the anesthesiologist with anterior to posterior pressure through the mouth on the anterior ring of C1, or posterior to anterior pressure from underneath. If the fracture is high in the odontoid, the threads of a partially threaded screw may cross the fracture preventing compression. Either cutting the tip of the screw to shorten or use of a fully threaded screw with overdrilling to the fracture site prevents this problem. If problems occur before or during the procedure, it may be necessary to abandon attempts at fixation of the fracture and switch to a primary C1–C2 posterior fusion.

Pitfalls

- Malreduction of the odontoid fracture prevents fracture site compression and adequate stability. Redisplacement or pseudarthrosis is likely to occur.
- Significant osteoporosis, comminution at the fracture site, or failure to gain purchase on the cortical bone at the tip of the odontoid fragment can prevent compression and diminish stability.
- Incorrect starting position can lead to poor screw position and fixation or redisplacement of the fracture. A starting point that is too anterior may predispose the screw to break out of the C2 body anteriorly and allow posterior angulation or displacement of the proximal fragment.
- A guidewire may be used, with caution, to gain and hold initial fracture reduction for overdrilling. If there is a slight bend in the guidewire, caused by minor deflections as it is passed up the odontoid, the drill will bind the guidewire as it is advanced and dangerously advance it out through the tip of the odontoid.

21 Anterior C1, C2 Arthrodesis: Lateral Approach of Barbour and Whitesides

Michael Schiraldi, Eli M. Baron, and Alexander R. Vaccaro

21.1 Description

The lateral retropharyngeal approach to the upper cervical spine was developed by Kelly and Whitesides as an alternative approach to the anterior cervical spine, avoiding the complexities of anterior extrapharyngeal approaches, which require dissection medial to the carotid sheath or dislocation of the mandible. This approach is actually done posterior to the carotid sheath, avoiding branches of the carotid artery and the facial nerve. Additionally, the technique allows access from C1 to T1 and avoids the potentially higher morbidity of a transoral/transpalatal approach. Anatomical advantages over posterior screw fixation of C1–C2 include sparing of the posterior musculature and the lack of dependence on the C2 pars diameter for performing the procedure.

21.2 Key Principles

The lateral approach of Barbour and Whitesides for C1, C2 arthrodesis allows for atlantoaxial stabilization when an anterior approach is required, such as when the posterior elements are not competent. This allows for access from C1 to T1 without the technical hurdles of extrapharyngeal approaches and morbidity of transoral operations. Biplanar fluoroscopy is recommended, although a single C-arm may be used if necessary. Preoperative computed tomography (CT) scans are used to accurately determine screw lengths.

21.3 Expectations

Adequate stabilization of the atlantoaxial joint via a stand-alone C1–C2 anterior arthrodesis, avoiding the morbidities of a high extrapharyngeal or transoral approach

21.4 Indications

This surgery is indicated when there is instability at C1–C2 requiring anterior fixation or when an anterior approach is required for a diagnosis. The approach is advantageous over transoral surgery, where fixation is necessary for instability and a posterior approach is contraindicated (presence of posterior infection or incompetent posterior elements). This procedure may also be useful as a salvage technique following failed posterior arthrodesis. Alternatively, a technically less-demanding procedure may be anterior C1–C2 transarticular fixation (▶ Fig. 21.1). This is also performed via an anterior retropharyngeal approach. In a manner similar to that of an odontoid screw placement, the incision is made at the C5–C6 level. Biplanar fluoroscopy with K-wire placement is used prior to placing cannulated lag screws.

21.5 Contraindications

- Vertebral artery injury
- Local infection
- Inexperience with regional anatomy

21.6 Special Instructions, Positioning, and Anesthesia

The patient is placed in the supine position. Fiberoptic nasotracheal intubation is preferred in cases of significant instability. Intraoperative neurophysiologic monitoring, including somatosensory evoked potentials and transcranial motor evoked potentials, if available, is used during positioning and throughout the procedure. Dental occlusion should be maintained to keep the angle of the mandible from limiting the area of dissection.

Biplanar fluoroscopy or frameless stereotaxy may be useful during guidewire insertion, drilling, and screw placement to ensure proper instrumentation while limiting the risk of neurovascular injury.

For positioning, unless contraindicated, the neck should be rotated to the opposite side and extended as much as possible.

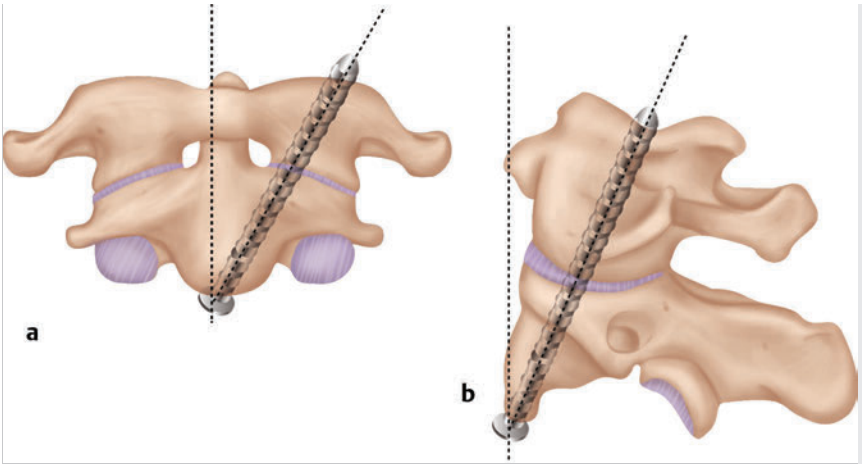

Fig. 21.1 **(a)** Anterior and (**b**) lateral views of screw trajectory inserted via the anterior transarticular approach. This is done in a manner similar to odontoid screw placement with the incision at the C5–C6 level.

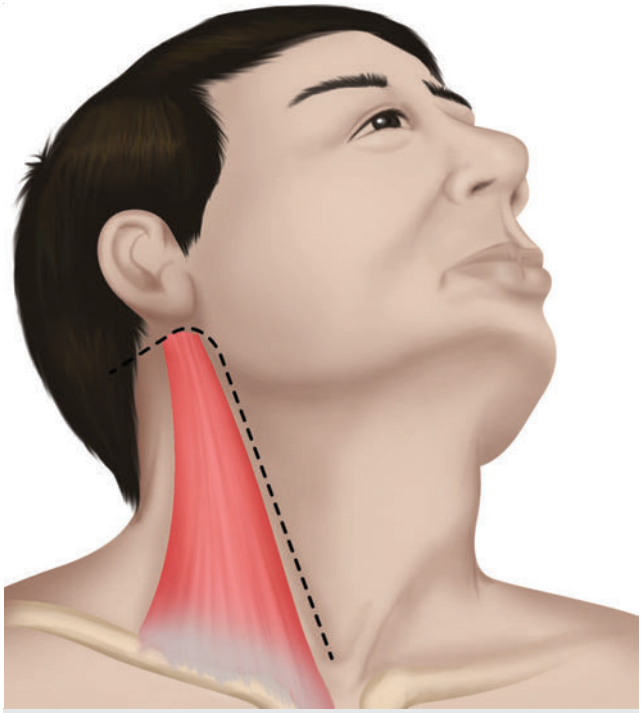

Fig. 21.2 Hockey-stick incision (dotted line) used for the lateral approach to the upper cervical spine.

The earlobe can be sewn anteriorly to the cheek to facilitate exposure of the field. Postoperative prophylactic tracheostomy should be considered in cases where there is significant retropharyngeal dissection. Performance of the tracheostomy after the procedure is usually more convenient.

21.7 Tips, Pearls, and Lessons Learned

Preoperative imaging and planning are essential prior to performing the procedure, which includes CT for studying bony anatomy and estimating screw length. Computed tomography angiography and magnetic resonance angiography (MRA) are useful noninvasive modalities for assessing the position and patency of the vertebral arteries.

21.8 Difficulties Encountered

- Avoid the parotid gland, which may be seen superficially at the cranial end of the incision. Dissection into the gland may result in facial nerve injury or parotid fistula. Also, deep at the cephalad end of the incision lies the posterior belly of the digastric muscle. Care should be taken to avoid retraction against this muscle to minimize risk of injury to the facial nerve, which lies between the digastric muscle and the base of the skull.
- Excessive medial retraction on the nasopharynx may result in mucosal laceration and subsequent contamination of the field.
- Excessive retraction may contribute to postoperative dysphagia and possible cranial nerve injury, including the hypoglossal and superior laryngeal nerve.
- Excessive retraction on the spinal accessory nerve should be avoided to minimize risk of sternocleidomastoid or trapezius weakness.

21.9 Key Procedural Steps

21.9.1 Step 1

A hockey stick-shaped incision is made from the tip of the mastoid process and taken distally along the anterior border of the sternocleidomastoid muscle (▶ Fig. 21.2). The greater auricular nerve is identified as it crosses the sternocleidomastoid muscle and dissected proximally and distally to increase its mobility, facilitating retraction. If needed, it may be divided with a resultant small sensory deficit around the ear. The external jugular vein is also ligated and divided.

21.9.2 Step 2

The platysma is divided parallel with the prior incision, followed by division of the deep cervical fascia investing the sternocleidomastoid. The sternocleidomastoid muscle is detached from the mastoid process. This is done by incising it transversely as it inserts onto the mastoid process and then everting it. The spinal accessory nerve is then identified, about 3 cm from the tip of the mastoid process. The nerve should then be protected with a vessel loop. Triggered electromyographic monitoring may facilitate its identification. The internal jugular vein is located in the carotid sheath and dissected from the spinal accessory nerve for greater mobilization. The sternomastoid branch of the occipital artery is identified next, distal to the spinal accessory nerve, and is ligated. Both the spinal accessory nerves and the internal jugular veins are dissected proximally to the digastric muscle. The dissection continues posterior and lateral to the carotid sheath and medial to the spinal accessory nerve and sternocleidomastoid muscles (▶ Fig. 21.3).

21.9.3 Step 3

Dissection continues transversely along the anterior border of the transverse processes. Sharpey fibers, which attach the midline viscera to the prevertebral fascia and muscles, are divided to enter the retropharyngeal space. Blunt dissection with a peanut is used to clear the prevertebral fascia. The C1 arch is easily located by palpating its prominent transversely oriented anterior arch. C2 can also be located by palpation, as it has a prominent vertical ridge at its base. A subperiosteal dissection of C1 and C2 is then performed where the longus colli and longus capitis muscles are stripped laterally. The longus colli muscle may be detached from its origin on the anterior surface of C1–C2 to maximize exposure. The intertransverse membrane at C1–C2 should not be violated. The approach and dissection are then repeated on the contralateral side. The facets are then exposed through blunt dissection. A small cutting bur and cervical curettes are used to denude the cartilaginous C1–C2 articulation, and the joint space is packed with autogenous iliac crest bone graft.

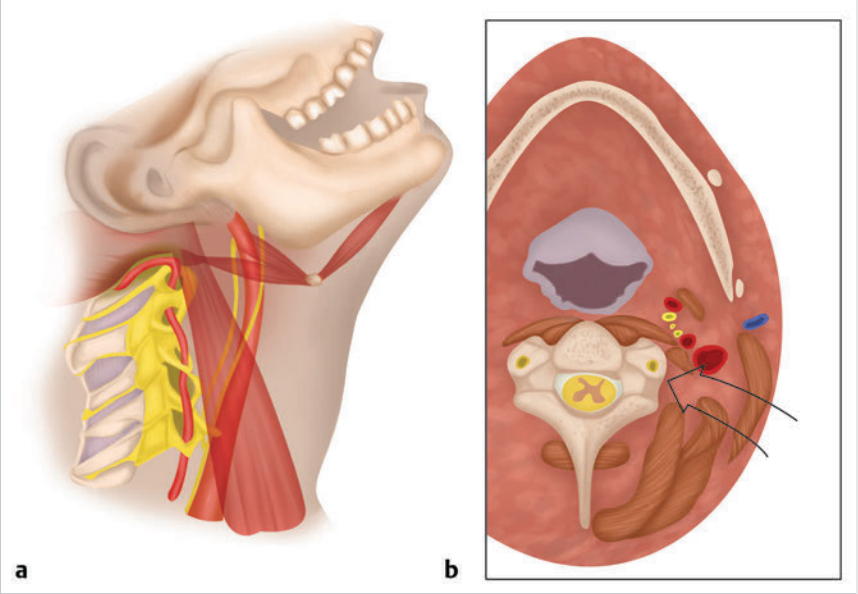

Fig. 21.3 **(a)** Lateral approach to the upper cervical spine. (**b**) Transverse section showing approach to the C1–C2 joint. Muscles to be retracted or transected are shaded.

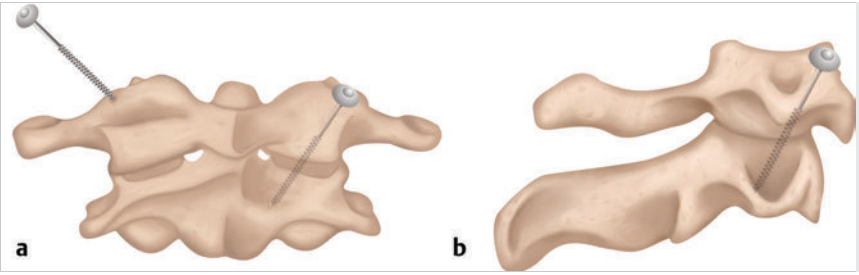

Fig. 21.4 **(a)** Anterior and (**b**) lateral views of screw trajectory through the C1–C2 facet joints.

21.9.4 Step 4

Screw fixation is now performed. A 2-mm guidewire is placed at the anterior base of the C1 transverse process, aiming 25 degrees from superolateral to inferomedially in the coronal plane and 10 degrees posteriorly in the sagittal plane. At the starting point, the guidewire should be in line with the ipsilateral mastoid process. Biplanar fluoroscopy should confirm wire placement. Drilling is then performed with a cannulated drill, first using a 2.7-mm cannulated drill bit over the guidewire followed by a 3.5-mm cannulated drill bit that is taken through only the C1 lateral mass for a lag technique. Alternately, a lag screw may be used. The procedure is then repeated on the opposite side. A 3.5-mm tap is used followed by a 3.5- by 26-mm cannulated screw, in the average adult. Preoperative CT measurements, however, are essential in estimating appropriate screw length (▶ Fig. 21.4).

21.9.5 Step 5

Meticulous hemostasis is obtained, followed by reapproximation of the sternocleidomastoid muscle to the periosteum overlying the mastoid process. A drain should then be placed followed by customary closure of the platysma and skin. At this point, prophylactic tracheostomy should strongly be considered. Postoperatively the patient should be maintained in a Philadelphia collar.

21.10 Bailout, Rescue, and Salvage Procedures

The definitive salvage procedure for a failed C1–C2 anterior arthrodesis is an occipitocervical arthrodesis. Should a vertebral artery injury occur, packing with Gelfoam (Pfizer Pharmaceuticals) or SURGICEL (Johnson & Johnson) should be done for tamponade, and intraoperative neurovascular consultation should be obtained. The contralateral procedure should be aborted.

Pitfalls

- Excessive retraction can lead to dysphagia/cranial nerve injury.
- Penetration of the spinal canal can lead to spinal fluid leakage or neural injury.
- Injury to the spinal accessory nerve during dissection may cause ipsilateral trapezius or sternocleidomastoid weakness.
- Horner's syndrome may result from excessive lateral dissection, especially if a strictly subperiosteal plane is not maintained.
- Injury to the parotid gland or digastric belly may result in facial nerve palsy.

22 Placement of Cervical Mesh and Expandable Cages

Eric Giang, Eric Chen, and Kris Radcliff

22.1 Description

Mesh and expandable cages serve to recreate axial spine support following cervical corpectomy. Cervical corpectomy is commonly performed for the treatment of cervical spine of complex retrovertebral pathology, ossification of the posterior longitudinal ligament (PLL), trauma, infection, deformity from metastatic disease and resection, and myelopathy. Anteriorly based approaches offer ease of decompression and allow for placement of appropriate bone graft. Various grafting choices include the gold standard tricortical iliac crest autograft and allografts including fibular strut allografts.

22.2 Key Principles

Mesh cages and expandable cages theoretically eliminate the complications associated with harvesting iliac crest autograft. Structural cages enable utilization of local autograft from the corpectomy, potentially increasing the fusion rate versus structural allograft alone. Cages were designed to replicate native vertebral body function to protect the spinal cord by providing stability and resistance to axial loading. Cages contain a large interbody–bone interface to promote fusion at the endplates, and also have the ability to resist migration while maintaining sagittal alignment and vertebral height. Preoperative planning and templating may therefore assist in selecting the proper size implant. These cages are essential when other options such as structural allograft are impossible due to the defect size (such as a multilevel corpectomy).

Implantation of nonexpandable cages can be technically demanding. Cages often come prefabricated in certain sizes and require trimming to properly fill the defect to avoid overdistraction. Intraoperative implant dislodgement requires removal and repositioning, which places the integrity of the endplate at risk. Expandable cages were developed in an attempt to address the challenges of a nonexpandable mesh cage. Graft window sizes in expandable cages are usually smaller to accommodate for the expandable mechanism. As a result, the implant–bone interface also is compromised, owing to the increased bulk of the expandable cage in turn limiting the surface area that is ideal for fusion.

22.3 Expectations

Clinical studies have demonstrated excellent fusion results in patients undergoing anterior cervical corpectomy with titanium expandable cages demonstrating minimal subsidence. The ability to adjust the expandable cages in situ results in a better fit than traditional nonexpendable cages. In addition, donor-site–related complications are avoided through utilization of local autograft from the corpectomy site.

22.4 Indications

Mesh and expandable cages can be used to fill corpectomy defects resulting from the following:

- Fractures
- Tumors
- Degenerative spondylitic disease
- Ossification of the PLL

22.5 Contraindications

Mesh and expandable cages are not recommended when the defect is too small for the implant and in the setting of pyogenic infection in general.

22.6 Special Considerations

- Preoperative templating is essential in the utilization of cervical vertebral body replacement cages. The surgeon should measure the cranial caudal vertebral body height of the intended corpectomy defect (from endplate to endplate). The surgeon should also measure the endplate footprint size including the anteroposterior and mediolateral dimensions. Computed tomography is the best imaging modality for such measurements and also enables identification of aberrant vertebral artery anatomy. Many surgeons utilize just magnetic resonance imaging for these measurements to avoid patient radiation exposure.
- Measurement and templating will enable the operative room staff to have the most likely sizes available and reduce lost operating room time following the corpectomy when there is usually significant bleeding. Additionally, once the corpectomy is performed, measurement of the defect can be difficult because it is easy to overdistract or underdistract.
- If possible, our preference in the cervical spine is utilization of mesh cages (overexpandable cages) packed with bone graft because they offer a larger window for packing with bone graft and an excellent endplate–graft interface.
- Overdistraction of the interspace will result in cage kickout or subsidence. Some expandable cages are “powerful” and have the capacity to distract the interspace significantly. Preoperative templating will enable the surgeons to prevent overdistraction.

22.7 Special Instructions, Positioning, and Anesthesia

- Patients are positioned supine with an expandable intravenous bag under the shoulders to create gentle lordosis.
- Total intravenous general anesthesia (TIVA) is utilized. Our preference is multimodal neuromonitoring with somatosensory and motor evoked potentials.

22.8 Tips, Pearls, and Lessons Learned

- We apply Gardner-Wells tongs to the skull prior to the corpectomy attached to a rope.

- Perform diskectomies above and below the intended corpectomy levels. Size the endplates once the diskectomies are performed, before the corpectomy is commenced.
- Use the widest endplate implant possible to increase surface area for stability.
- During cage impaction we ask anesthesia staff to add a 10-lb weight to the Gardner-Wells tongs to maintain gentle distraction and ease of cage placement.
- Calipers can be difficult to utilize in the setting of a multilevel corpectomy depending on the extent of the exposure. Instead of using calipers to measure the corpectomy defect, we cut the paper ruler (that often accompanies a surgical marking pen) to the suspected corpectomy defect length and place it into the corpectomy defect in the wound to size the defect precisely.
- If the cage does not seat deeply enough in the corpectomy defect, carefully inspect the lateral walls of the corpectomy. If the corpectomy is wider anteriorly than posteriorly (creating a trapezoidal axial cross section), the cage will not seat deep enough into the corpectomy trough. If so, the corpectomy has to be widened in line with the uncovertebral joints (to effect a rectangular axial cross section). This potential complication is more likely with mesh cages and expandable cages than with allograft or autograft because the bone grafts are usually also wider anteriorly versus posteriorly and can occasionally fit into a trapezoidal defect.
- Test the cage stability once placed in situ by grasping with a Kocher clamp or hemostat and tug anteriorly. The cage should not slide anteriorly during this maneuver.

22.9 Difficulties Encountered

- Aggressive endplate preparation or poor bone stock from metastatic pathology may lead to cage subsidence.
- Do not disrupt the subchondral bone as that may lead to implant subsidence.
- A loose cage fit can result from overdistraction, cutting the mesh too short, or from failure to seat the corpectomy graft deeply enough. In this case, loosen the distraction and determine the cause for the loose cage fit; if necessary, recut the mesh for a longer cage instead of accepting a loose fit. Use a paper tape measure cut at the intended corpectomy mediolateral dimensions (usually 15–18 mm) to ensure that the corpectomy is wide enough throughout. The cage must ultimately fit snugly in the corpectomy defect.

22.10 Key Procedural Steps

- Anterior cervical corpectomy can be approached via a standard Smith-Robinson approach.
- For single-level corpectomies, a transverse incision is usually sufficient; however, consider a longitudinal incision along the medial border of the sternocleidomastoid muscle for more extensive corpectomies.
- Once the desired surgical level is properly identified on spinal imaging, expose the anterior vertebral body cortex out to the borders of the uncovertebral joints.
- Diskectomies are performed above and below the intended corpectomy level(s).
- The diameter of the endplates is measured using circular endplate sizing trials; the scrub nurse at this point can begin to assemble the likely implants.
- A corpectomy is performed in the usual fashion.
- The endplates are decorticated to expose bleeding bone without damaging the subchondral bone.
- Traction is applied by the anesthesiologist to the Gardner-Wells tongs. In the event of a single vertebral level, Caspar pins may be utilized instead to effect distraction, but this becomes technically difficult in multilevel corpectomies.
- The length of the required implant is measured with a tape measure.
- If a mesh cage is used, it is cut to the appropriate length and packed with local bone from the corpectomy.
- If an expandable cage is used, it is packed with bone and inserted and expanded.
- The cage fit is tested with a Kocher or hemostat.
- Lastly, often an anterior plate is placed or screws are placed through the expandable cage device into the bordering vertebral levels.

22.11 Bailout, Rescue, and Salvage Procedures

- Some expandable cages have a built in plate-screw capacity. Consider these implants if there is concern about cage stability.
- Anterior instrumentation is biomechanically weaker than posterior fixation. Consider posterior fixation if indicated in such cases as poor bone quality, multilevel corpectomies, or poor cage stability.

Pitfalls

- Anterior “buttress plates” have a high failure rate; if anterior plating is used, attempt segmental fixation if at all possible.
- Use of a fixed screw anterior cervical plate may result in paradoxical cage loading (axial loading in extension and unloading in flexion) due to a tension band effect. This may increase the risk of cage dislodgement or subsidence.
- Avoid using a mesh or expandable cage in the setting of a partial corpectomy if possible, as the implants are at high risk of subsidence into cancellous bone. Do not overly expand an expandable cage or place an oversized fixed size cage into a corpectomy site. Overdistraction will lead to endplate failure. We place corpectomy cages with manual traction only (no Caspar traction pins).

23 Placement of Anterior Low-Profile Cervical Interbody Spacer and Screws

Eric Giang, Eric Chen, and Kris Radcliff

23.1 Description

Since its introduction by Smith and Robinson, anterior cervical diskectomy and fusion (ACDF) has evolved with many technical modifications. Recently, a variety of novel implants have been introduced to reduce the invasiveness of the procedure while maintaining similar stability to open surgery. Stand-alone anchored spacers offer an alternative to ACDF with anterior plating, providing low-profile fixation.

23.2 Key Principles

Cervical spine surgery relies on principles of anatomical and soft tissue tension restoration, stable fixation to promote fusion, and decompression of the neural elements. Traditionally, cervical fusion with stand-alone interbody cages (without plating) provided stability in compression and axial loading, but offered little stability in extension, axial rotation, or lateral bending. The absence of plate fixation may lead to micromotion between the cage and the endplate, increasing the risk of pseudarthrosis. The addition of anterior plating provides increased stability and rates of fusion, but is not without complications. They include adjacent-level degeneration, esophageal injury, vertebral artery injury, dural tear, postoperative airway compromise, spinal cord injury, hematoma formation, dysphagia, dysphonia, and graft dislodgement. Postoperative dysphagia ranges from 2 to 67% and may be due to retraction technique, increased operative times, anterior instrumentation prominence, preoperative neck or shoulder pain, age > 60 years, female sex, deformity correction and resultant change in prevertebral tissue tension, or postoperative pain. However, dysphagia may simply be a result of any open cervical procedures as demonstrated in those with postoperative dysphagia following posterior approaches. Stand-alone anchored spacers were developed to address the potential problems caused by traditional plating from prominent hardware.

Although the true etiology remains debatable, adjacent segment disease is a recognized occurrence following ACDF with anterior plating and may be caused by hardware encroachment or perhaps the natural progression of cervical spondylosis. Anterior plating helps minimize pseudarthrosis of a fused segment, maintain spinal alignment, and has demonstrated shorter time to fusion; however, three- and four-level cervical fusions with stand-alone implants have demonstrated acceptable results with minimal subsidence.

23.3 Expectations

Stand-alone anchored implants without plating eliminate the concern for hardware prominence by negating the need for anterior plating and may potentially diminish concerns regarding adjacent segment disease. Additional fusion adjacent to preexisting anteriorly plated fusions can be accomplished without plate removal or longer plates due to a lower profile design. Obliquely oriented screws help firmly secure the stand-alone anchored implant within the disk space and reduce the risk of migration. These screws provide similar biomechanical stability found in traditional spacers with anterior plating. Maintaining sagittal alignment along with less prominent hardware while achieving stable fusion can be accomplished with these novel low-profile stand-alone implants. Preparation of the anterior surface of the vertebral body is not required, which may reduce operative times compared to traditional plating.

23.4 Indications

The lower profile nature of cervical arthroplasty appears to help lower long-term dysphagia and may be applicable to low-profile cervical interbody spacers.

Stand-alone anchored spacers share similar indications to traditional ACDF with anterior plating. Currently, stand-alone anchored spacers are approved by the Food and Drug Administration for single-level placement in only the following circumstances:

- Degenerative disk disease
- Spinal stenosis
- Failed previous fusions
- Pseudarthrosis

23.5 Contraindications

- Spinal fracture
- Spinal tumors
- Spinal osteoporosis
- Spinal infection

23.6 Special Considerations

Subsidence is a concern inherent in cervical fusion regardless of implant choice. Without proper endplate support of an implant, subsidence could potentially lead to kyphotic deformities, pseudarthrosis, and ultimately a recurrence of symptoms. Factors contributing to subsidence in both stand-alone implants and mesh and expandable cages include intraoperative overdistraction, distance of the implant from anterior rim, contact area of implant, and amount of bone removed during endplate preparation.

23.7 Special Instructions, Positioning, and Anesthesia

After induction of general anesthesia, position the patient supine on the operating table with the neck in slight extension with the assistance of a small sandbag or roll. Position the airway away from the operative field. Then identify the level

of skin incision using either radiographic or anatomical landmarks.

23.8 Tips, Pearls, and Lessons Learned

- The screw length is usually longer (16 mm) than traditional ACDF screws (14 mm).
- Use a wide implant to optimize the potential fusion surface.

23.9 Difficulties Encountered

Placement of stand-alone anchored spacers can be difficult at the cranial and caudal extremes due to the angles required for screw placement.

23.10 Key Procedural Steps

Generally, less exposure of the vertebral body is required compared to a traditional anterior cervical plate due to the lower profile placement of the implant. The diskectomy is performed as usual with curettes and rongeurs. The posterior longitudinal ligament is incised. Then insert the appropriate trial spacer and verify under fluoroscopy its depth and position. The device should seat approximately 2 mm behind the anterior column in the lateral view and centrally in the anteroposterior (AP) view. Select the corresponding implant and fill with bone graft until packed tightly. Introduce the implant into the disk space using distraction of the vertebral bodies until it is at the appropriate AP position. Then introduce a drill guide into the device and drill the screws cranially and caudally to secure the implant. Finally, tighten the screws according to the manufacturer's recommendations.

23.11 Bailout, Rescue, and Salvage Procedures

Although traditional ACDF has been described in flexion-distraction injuries of the cervical spine, stand-alone anchored spacers (without plating) have never been evaluated in cervical trauma. It has been recommended that additional external immobilization be considered in the setting of locked screw configurations and cervical trauma as only 66% of motion is reduced compared to intact specimens. Variable-angle configurations in the setting of cervical trauma provided minimal stabilization. Current indications do not include cervical trauma, but more importantly two screws with the variable-angle configuration was inferior to the four-screw-locked configuration.

Pitfalls

- Do not overdistract the disk space.
- Do not resect the endplates as subsidence will result in rotation of the implant in the sagittal plane and the caudal screws will encroach upon the spinal canal.
- Leave the implant proud to engage the screws in the apophyseal ring. If the implant is flush with the anterior vertebral body margin, then the screws will miss the apophyseal ring.

24 Anterior Cervical Plating: Static versus Dynamic

Andrew A. Indresano and Paul A. Anderson

24.1 Description

Anterior cervical plating provides stabilization of the cervical spine after arthrodesis. Theoretical advantages of plate fixation include improved initial stability and fusion success with one- and two-level fusions as well as decreased complications from graft dislodgement, endplate fractures, and late kyphotic collapse. Modern plates have the capacity of screw capture, thereby preventing loosening, which requires only unilateral screw purchase. Plating systems can be static or dynamic. Static plates have a rigid connection between screw and plate and do not allow motion during healing. Dynamic plates allow change in plate length to accommodate changes in the interbody graft that occurs following implantation.

24.2 Key Principles

During healing of interbody cervical fusions, graft resorption of 1 to 2 mm per interspace occurs. Theoretically, plates may unload the graft or shield it from stress, and may lead to nonunion or plate failures. This is seen more commonly in longer fusions.

Cervical spine plates are classified as follows: (1) unrestricted backout, and (2) constrained (static) and semiconstrained plates that include two subclasses of (a) rotational and (b) translational. Unrestricted backout plates are of historical note. These were nonlocked, required bicortical screw purchase, and were associated with screw backout. They are not currently recommended. The constrained or static plates are locked screw interface that allow unicortical fixation without screw backout (▶ Fig. 24.1). Dynamic or semiconstrained plates have been developed that allow axial settling to accommodate a potential biologic or mechanical shortening of the anterior graft (▶ Fig. 24.2). Rotational plates allow rotation or toggle at the plate-screw interface. The translational plates offer locked bone–screw interfaces with the ability to translate along the long axis to accommodate shortening (▶ Fig. 24.3). Several mechanisms are available including plates that have oval holes allowing translation through the holes, whereas others have screws fixed to the plate and translation occurs by plate shortening (▶ Fig. 24.4).

Anterior cervical plates are load-sharing devices that require a graft or other interbody device. Cadaveric biomechanical load transmissions through the graft were found to be higher with dynamic (60–80%) versus static plates (53–57%). This was accentuated when the graft was undersized (dynamic 50–57% vs. static 17%). Therefore, one may hypothesize that a dynamic plate will lead to high union rates when the graft is appropriately loaded. The lack of load sharing over time in static plates may lead to hardware fatigue or loosening. Still unknown, however, is the critical amount of load sharing to allow bony union. What is known is that strain rates of less than 5 to 6% lead to union, while strain rates of > 10% lead to nonunion. Thus, plate fixation must limit strain and optimize load sharing to allow healing.

24.3 Expectations

Anterior cervical plates result in higher fusion rates, prevent graft collapse, and maintain spinal alignment. A low rate of hardware-related complications should occur. Similar clinical outcomes should be expected for single- or multi-level fusion with static versus dynamic plating.

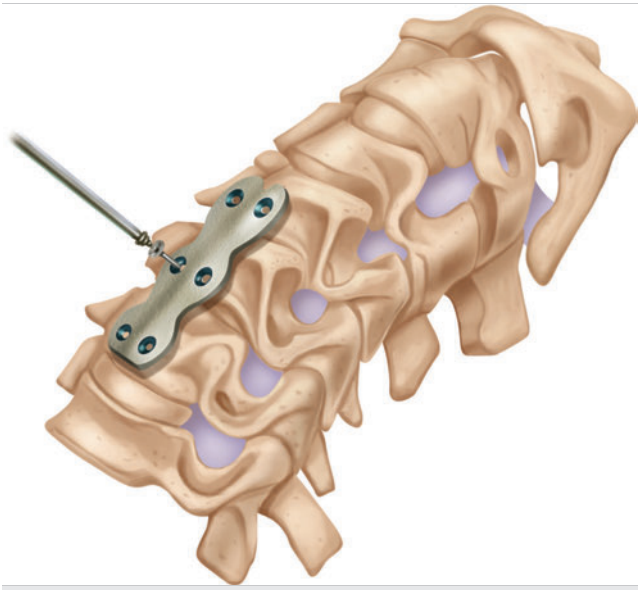

Fig. 24.1 Placement of a statically locked plate.

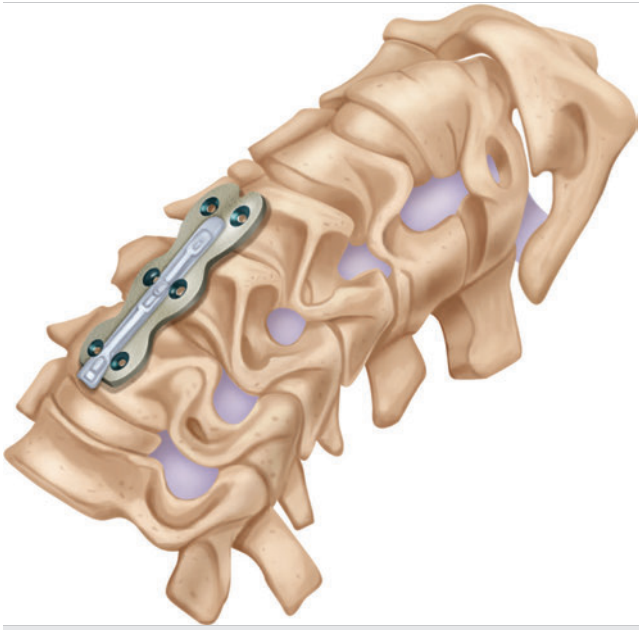

Fig. 24.2 Placement of a dynamic plate, allowing translation.

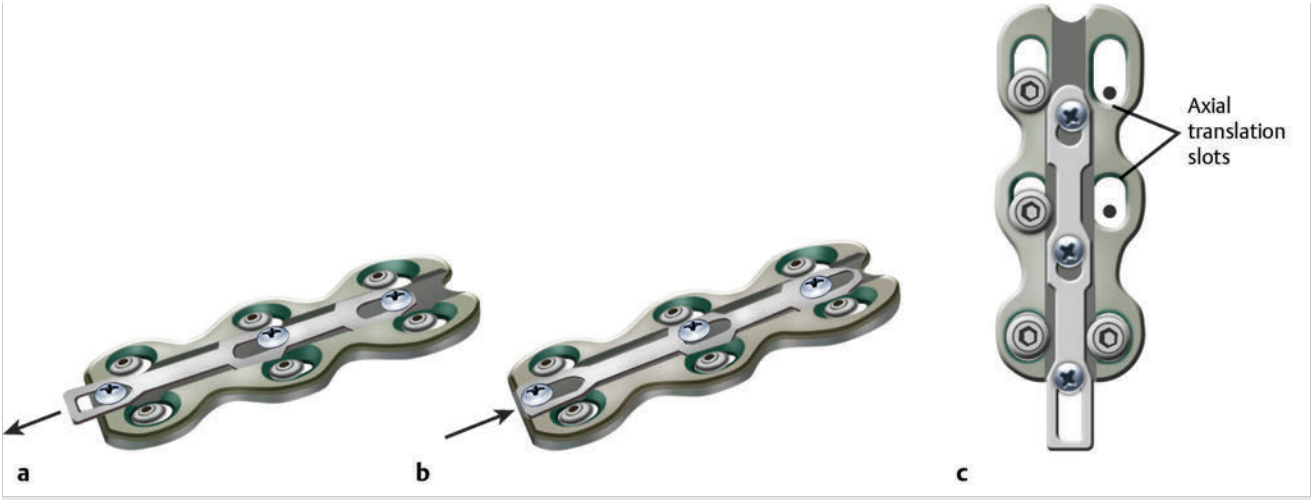

Fig. 24.3 (a-c) Examples of translation along the long axis to accommodate shortening.

24.4 Indications

Anterior cervical plate fixation has a wide range of indications. It is used to stabilize unstable conditions from trauma or other destructive lesions such as tumors. Its most common use is following decompression for degenerative conditions. It is thought to result in higher fusion success for two- and three-level cases. Its use following single-level fusion is controversial. Although evidence of efficacy in fusion success is conflicting, several investigations have demonstrated that plating for single-level cases results in a lower incidence of graft complications and maintains lordosis to a greater degree than do nonplated cases. Anterior plates can be used after both diskectomy and corpectomy.

Adequate evidence is not available to determine the role of dynamic versus static plates. Longer constructs such as three- or four-level fusions appear to have a high failure rate with static plates, the usual failure mechanism being screw loosening at the caudal end and graft dislodgment or intussusception. In these cases, if an anterior plate is used we recommend a translation plate, although one should be aware that this is controversial.

24.5 Contraindications

Static plates have a relative contraindication for use in long multilevel reconstructions secondary to early failure. Dynamic plating has been shown biomechanically to be weaker in trauma patients with significant posterior involvement. Dynamic plates have been found to be stable until the posterior longitudinal ligament is sacrificed, which resulted in significantly more range of motion (ROM) in flexion and extension and more axial ROM. This is of unknown clinical importance. A randomized study of patients with anterior and posterior injury found that anterior static plates resulted in similar outcomes with posterior cervical plates. The efficacy of translational plates in these patients is unknown.

Anterior plates should be used with caution in patients with osteoporosis, renal osteodystrophy, or severe kyphotic deformities, or in patients in a highly unstable condition with total ligamentous destruction, severe comminution, or missing posterior elements.

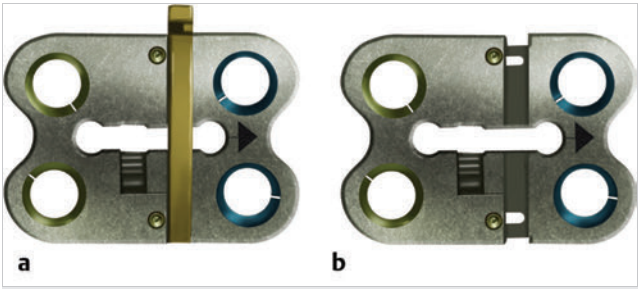

Fig. 24.4 (a, b) DynaTran (Stryker) anterior cervical diskectomy and fusion plate (**a**) with clip in place and **(b)** with clip removed to allow for plate compression.

24.6 Special Considerations

If patients have severe osteoporosis or rheumatoid arthritis that compromises fixation, one may consider either supplemental posterior fixation or more rigid immobilization postoperatively with close radiographic follow-up.

24.7 Special Instructions, Positioning, and Anesthesia

Anterior diskectomy and fusion is performed with the patient in the supine position on a standard table (see **Video 24.1**). The head is held with a horseshoe head holder, with the neck slightly extended. A shoulder roll can be placed either transversely or longitudinally, based on surgeon preference to aid in neck extension. Three-inch cloth tape is used to lower the patient's shoulders bilaterally. The endotracheal tube should be taped to the right side of the mouth (assuming a left-sided approach is being performed). Verify that once the patient is

positioned, the patient is symmetric before sterile preparation and draping. In trauma patients, reduction should be performed prior to plating. For reduction assistance either tong axial traction or Mayfield tongs (for better rotational control) may be used based on surgeon preference.

24.8 Tips, Pearls, and Lessons Learned

Plates should be placed in the midline and have screws as close to the fused disk space as possible. Lateral placement can result in vertebral artery injury or intraforaminal screw placement. Midline placement can be determined based on location of uncovertebral joints or intraoperative anteroposterior radiographs. Most systems have temporary fixation pins that can maintain orientation while drilling and placing screws. If the patient is small, particularly small Asian women, sometimes even the smallest screws in the set are too long, so shorter screws need to be available.

The plates should lie as flush as possible on the spine. This often requires machining of the osteophytes or bony prominences. Plate length should be chosen to keep the plate 5 mm or more away from the adjacent level to avoid adjacent level ossification. Screw orientation should be parallel to the end plates to avoid crossing an unfused disk. Finally, to avoid iatrogenic spinal cord injury, make sure that when drilling any pilot hole to check the length of the drill bit protruding from the drill guide. This length should never be longer than the preoperative anteroposterior vertebral body distance measured based off preoperative imaging and/or can be directly measured intraoperative with a neuro-caliper depth bar.

24.9 Difficulties Encountered

Dysphagia is a common complication after anterior cervical diskectomy and fusion with plate fixation. Low-profile plates have been shown to minimize dysphagia postoperatively. Also, as noted earlier, osteophytes should be removed that would prevent the plate from sitting flat against the bone. In one study, retropharyngeal steroid (triamcinolone) on a collagen sponge has also been shown to decrease prevertebral soft tissue swelling and postoperative dysphagia without additional complication.

24.10 Key Procedural Steps

Once decompression is complete and the graft is properly placed, then plate placement is performed. Good carpentry of the graft–host interface is paramount for stability. The anterior osteophytes are burred down to allow a flat surface for the plate to sit. The plate size should be chosen carefully so that screws are placed adjacent to the end plates nearest the diskectomy/corpectomy. Lower profile plates have a lower incidence of dysphagia and should be used if possible. Screw length can be gauged from the vertebral body depth determined based on preoperative imaging or direct measurement with intraoperative calipers. Commonly, this length is 14 mm. Verify that the drill protruding from the drill guide is 14 mm prior to drilling to avoid catastrophic complications. If placing bicortical screws, use fluoroscopy to verify drilling and screw placement. Hold the plate in the midline while drilling so the plate does not shift. Eccentric plate placement can result in vertebral artery injury or screw placement that is intraforaminal. Lastly, obtain intraoperative radiographs to verify position of the plate prior to closure. Immobilization is controversial and depends on the injury, procedure performed and fixation obtained intraoperatively.

24.11 Bailout, Rescue, and Salvage Procedures

If screws have poor purchase, larger diameter screws or longer screw can be placed. Another option is bicortical screw placement. Alternatively, posterior fixation can augment the anterior plate.

If hardware is loose or screws are seen to be backing out, early revision is recommended.

Pitfalls

- Specific pitfalls of anterior cervical plating include hardware failure or misplacement, pseudarthrosis, dysphagia, and esophageal erosion. Radiculopathy or vertebral artery injury can be the result of a misdirected screw. Dynamic plates are intriguing in their ability to settle and accommodate graft subsidence. However, a dynamic plate cannot substitute for good carpentry of the graft–host interface with regard to initial stability or potential union rates. Act early if loose hardware is noted on radiographs, as this can erode into the esophagus if not revised in a timely fashion.

Section V

Posterior Thoracic Decompression

25 Transpedicular Decompression *82*

26 Costotransversectomy *85*

27 Lateral Extracavitary Approach *89*

V

25 Transpedicular Decompression

Rafael A. Buerba, Michael C. Fu, Kingsley R. Chin, and Jonathan N. Grauer

25.1 Description

Transpedicular decompression is a technique to decompress the neural elements through a posterior approach in the thoracic spine.

25.2 Key Principles

The pedicle anatomically associated with the pathology of interest is taken down, allowing for access to the anterolateral canal, underlying disk, and posterolateral portion of the vertebral body.

25.3 Expectations

This technique allows access to pathology that may otherwise be difficult to access and potentially decreases morbidity that would be associated with strictly a posterior laminectomy, or more lateral costotransversectomy or anterior thoracic approach for the same pathology. In cases of intrapedicular lesions, it is the technique of choice.

25.4 Indications

- Fracture fragment reduction in the setting of spinal instability requiring posterior stabilization
- Posterolateral disk herniation
- Infection (including tuberculosis)
- Resection or biopsy of intrapedicular or vertebral body lesions

25.5 Contraindications

- Focal midline anterior spinal cord compression
- Central calcified disks (anterior or lateral approach preferred)

25.6 Special Considerations

As with any thoracic case, localization of level is of utmost importance. This requires appropriate preoperative image documentation and then intraoperative confirmation.

A complete laminectomy is not necessary for a unilateral approach, but is often performed for safe identification of the underlying anatomical structures and delineating the pedicle borders. The transverse process is generally taken to allow better visualization. Once the overlying bone has been removed, the edges of the pedicle can be palpated and an instrument can be passed medial to the pedicle for reference and to facilitate safe resection.

If complete facetectomy is performed and/or pedicle resection performed, posterior instrumentation/fusion is generally required.

25.7 Special Instructions, Positioning, and Anesthesia

Standard prone positioning is utilized on a radiolucent table, generally a Jackson table. Fluoroscopy is crucial for localization. Motor and sensory evoked potential monitoring is preferred. Anesthesia that allows for such monitoring, assuming it is used, is a must.

25.8 Tips, Pearls, and Lessons Learned

Vertebral level can be estimated counting from the 1st or 12th rib. Intraoperatively, confirmation of vertebral level is best achieved fluoroscopically by placing a radiopaque marker on the pedicle/transverse process overlying the area of interest. Spinous process markers tend to be less reliable. If it is difficult to localize the first or 12th rib and the area of interest on one fluoroscopic image, dropping spinal needles onto pedicles of identified levels and "walking" to the level of interest can be of help.

Once exposure is complete, the thoracic pedicle is identified by the intersection of the transverse process and lamina (▶ Fig. 25.1). Note that the pedicle is situated directly inferior to the superior articular process. Anatomical landmarks can be used as guides. For medial/lateral orientation, the lateral portion of the superior articular process corresponds to the lateral border of the pedicle. Further, the center of the pedicle is generally at the inflection of the transverse process to the lamina. For cephalad/caudad orientation, the pedicle is usually found along the ridge in the upper third of the transverse process. Laminotomy/laminectomy and resection of the transverse process will help facilitate visualization/palpation of the pedicle edges. Removal of the transverse process and lateral wall of the pedicle may enable greater visual line of sight to the midline. If it is difficult to define the path of the pedicle, the pedicle can be cannulated, as if for a pedicle screw, and this path can be a helpful reference.

A combination of fluoroscopy and palpation of the posterior aspect of the vertebral body along the medial border of the pedicle can be utilized to monitor the depth of the pedicle resection. The extent of resection is determined by the pathology being addressed (▶ Fig. 25.2).

If bone is resected from the posterolateral vertebral body, this can be grafted. However, as a greater amount of bone resection is required (depending on the underlying pathology), conversion to a broader exposure that allows for anterior column reconstruction may be considered (▶ Fig. 25.3).

25.9 Difficulties Encountered

Cancellous bone can cause significant bleeding during the course of such decompressions. This can be addressed with a

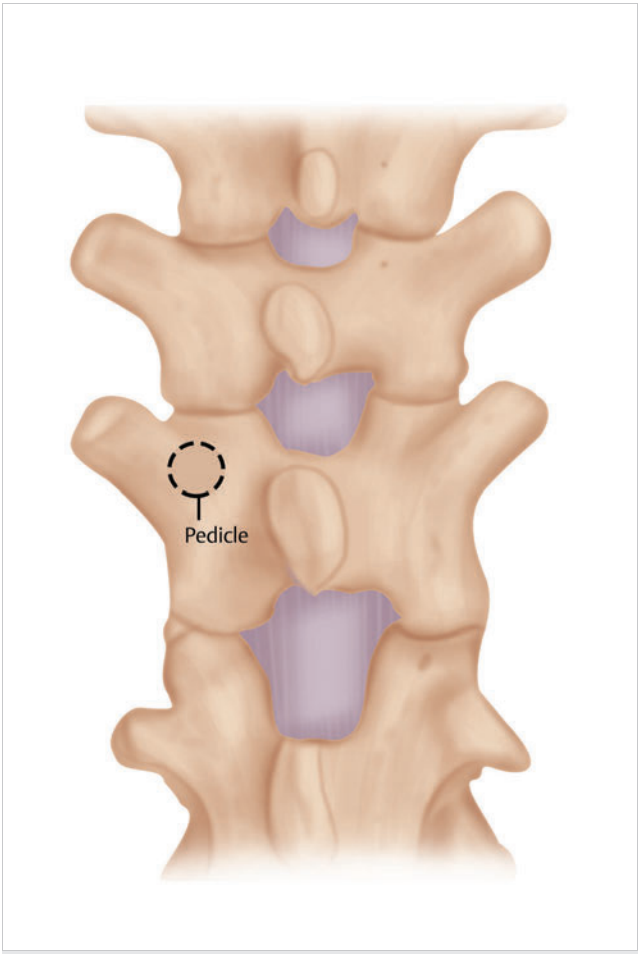

Fig. 25.1 Anatomical landmark of pedicle (circle).

combination of working expeditiously and using adequate hemostatic agents.

Neurologic elements are at risk with such exposures. Protection of such structures, as with any cord-level case, is crucial. This is best achieved by maintaining appropriate landmarks and protection of the neural elements. Neuromonitoring can help provide feedback.

25.10 Key Procedural Steps

Fluoroscopy is used to localize the incision and then for surgical confirmation. The exposure should include the entire lamina, transverse process, and costovertebral junction of the selected vertebra. Assuming instrumented fusion is planned, screws and

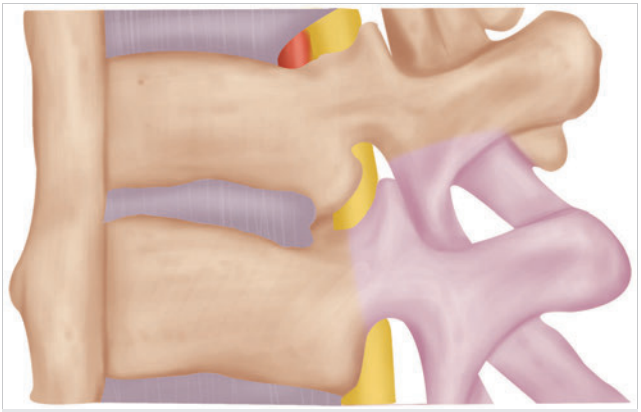

Fig. 25.2 Lateral view of thoracic spine. The colored bone shows the appropriate depth of pedicle resection as well as the extent of bone resection in a broad decompression.

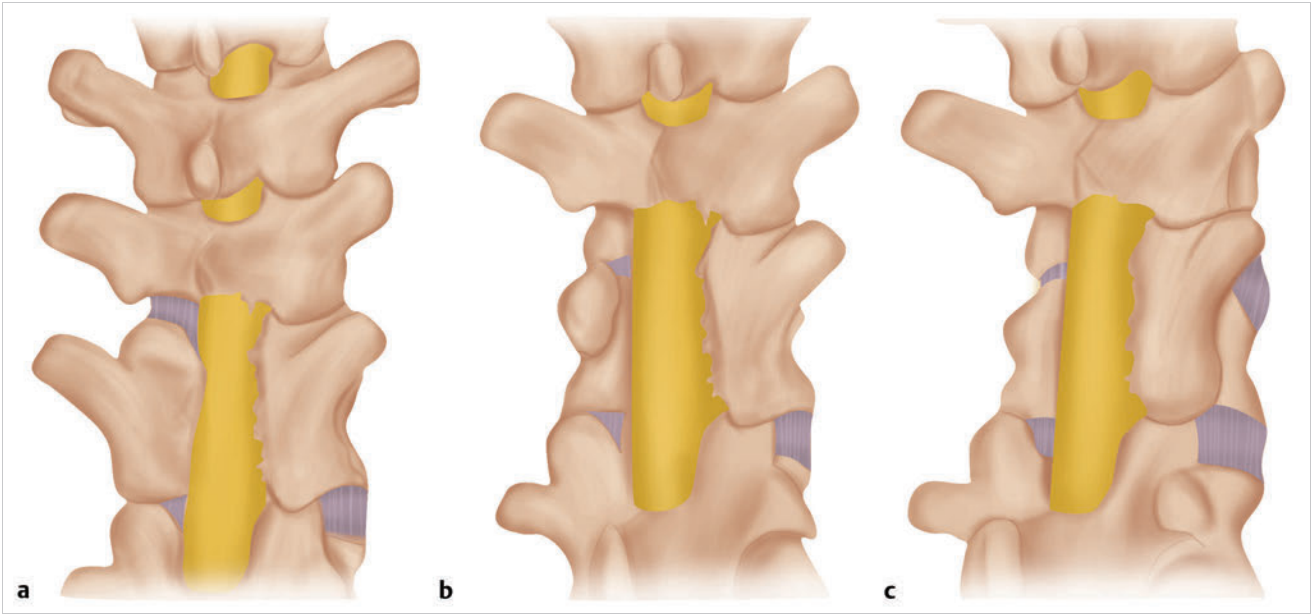

Fig. 25.3 Transpedicular approach with a broad exposure. (**a**) Laminectomy is followed by (**b**) resection of the transverse process and pedicle. (**c**) Completed pediculofacetectomy.

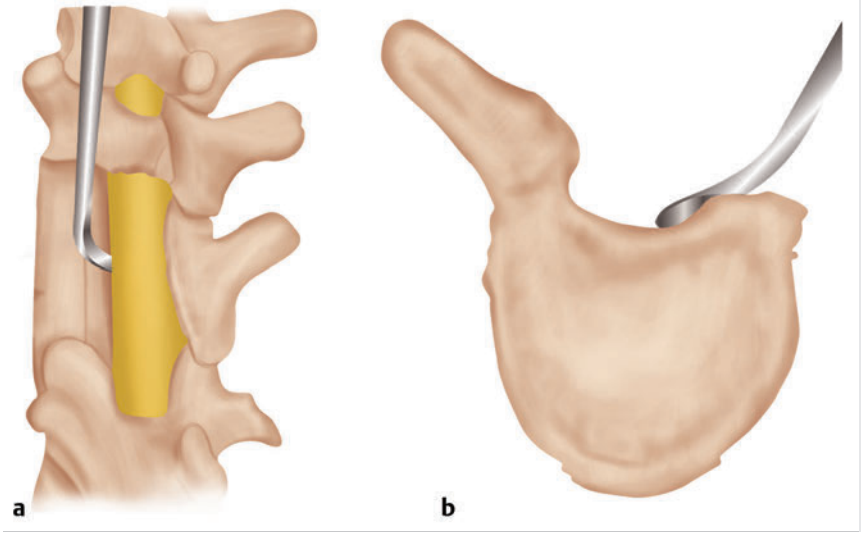

Fig. 25.4 Resection of lamina, facets, and pedicle allows for passage of reverse-angled curettes for safe displacement of the dura and inspection of the anterior spinal cord. (**a**) Posterolateral view and (**b**) cross-sectional view.

contralateral rod are generally placed prior to decompression. The ipsilateral rod is generally placed after the decompression.

A complete laminectomy may be performed over the involved vertebral body to identify the dura and exiting nerve. Excision of the facets overlying the pedicle is accomplished with a bur or rongeurs/Kerrisons. The pedicle is then removed using the bur down to the vertebral body (▶ Fig. 25.3), while protecting the exiting nerve root below. As noted in the section above, cannulating the pedicle prior to this step with a gear shift can provide a channel to follow.

Once the appropriate depth is reached (▶ Fig. 25.2) and localized fluoroscopically, the resection should allow passage of reverse angled curettes anterior to the thecal sac (▶ Fig. 25.4).

25.11 Bailout, Rescue, and Salvage Procedures

If adequate decompression is not achieved, remove more of the lateral pedicle or perform an extrapedicular approach. A costotransversectomy provides even greater access. If decompression is still inadequate, consider access from the contralateral pedicle if the lesion is accessible or convert to an anterior decompression.

Pitfalls

- Excessive bleeding
- Neurologic issues
- Incomplete resection of primary pathology

26 Costotransversectomy

Jeremy S. Smith and Mark J. Spoonamore

26.1 Description

Initially described for the drainage of paraspinal abscesses associated with tuberculosis, costotransversectomy is now utilized for a number of pathologies that require thoracic vertebral body access with concurrent exposure of the posterior elements. With this approach, an anterior decompression and fusion can be performed along with a posterior decompression of the posterior spinal canal. The approach has become quite useful for the treatment of many pathologies that traditionally have been treated with a staged anterior followed by a posterior approach. It has been described as a method to treat thoracic-level disk herniations, traumatic or pathologic vertebral fractures with retropulsion, osteomyelitis/diskitis, and rigid spinal deformities. It is particularly useful in patients that will not tolerate an open thoracotomy secondary to underlying pulmonary or intrathoracic pathology. Costotransversectomy allows for exposure of the thoracic spine in its entirety unlike a thoracotomy, which is limited by the diaphragm and thoracic inlet. Limitations of the costotransversectomy include direct access to anterior spinal cord pathology, which makes this approach less useful for midline compressive disease (▶ Fig. 26.1).

26.2 Key Principles

Costotransversectomy is a complex approach that requires a thorough knowledge of thoracic anatomy and experience with both anterior and posterior exposures. It is necessary to understand all of the potential complications that can be encountered and the appropriate management principles. It is a powerful alternative approach to open thoracotomy, but has visualization limitations that must be realized and applied prior to surgery by carefully assessing preoperative imaging studies.

26.3 Expectations

Costotransversectomy can be expected to provide a posterolateral directed corridor to the entire thoracic spine (T1–T12) with access to the anterior vertebral body, disk space, neural foramina, and spinal canal. The surgeon can access the anterior column to excise disk herniations, resect/debulk pathologic or compressive bone and soft tissue material, and subsequently fuse the anterior column. Access for posterior-directed decompression, instrumentation, and fusion is also available with this approach.

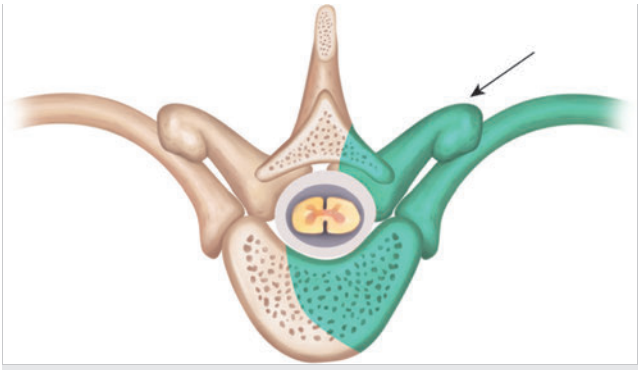

Fig. 26.1 Cross-section of costotransversectomy approach.

26.4 Indications

Most pathologies with anterior and posterior spinal element (or a combination of) involvement in the thoracic spine can be addressed with this exposure. Some common diseases treated include:

- Primary or metastatic tumors of the vertebral body or epidural space that require debulking or removal
- Partial or complete vertebral body resection for rigid deformity (kyphoscoliosis, congenital kyphosis, etc.)
- Thoracic disk herniation
- Traumatic conditions causing instability and spinal canal compromise osteomyelitis/diskitis
- Abscess drainage (paraspinal)
- Vertebral body biopsy

Patients who are being considered for an anterior approach (thoracotomy), but cannot tolerate it secondary to comorbidities are often optimal candidates for this approach.

26.5 Contraindications

Any pathology that requires:

- Direct midline anterior visualization adjacent to the dura
- Extensive anterior en bloc resection
- Extensive anterior fusion

26.6 Special Considerations

A thorough understanding of the three-dimensional pathoanatomy is essential to optimize exposure and limit complications. Particularly in cases with distorted anatomy, knowing exposure limitations will allow preoperative planning for alternative maneuvers and techniques that may assist in increasing the operative window (use of angled mirrors, endoscope, etc.). It is important that the lesion of interest be adequately visualized without applying any further traction or manipulation of the spinal cord that may cause a catastrophic neurologic injury.

Preoperative radiographic assessment requires sufficient imaging studies that will assist in intraoperative localization to the level of interest. To minimize the potential for wrong-level surgery, one consideration is to preoperatively have the interventional radiologist place a radiopaque marker in the vertebral body or pedicle of interest.

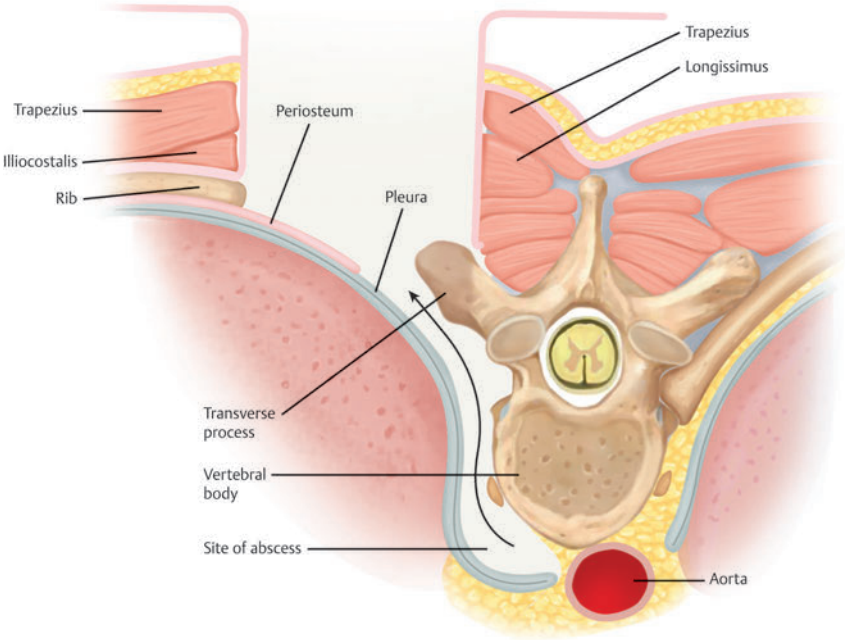

Fig. 26.2 Posterolateral access achieved by costotransversectomy.

26.7 Special Instructions, Positioning, and Anesthesia

Multiple position variations have been described including prone, lateral decubitus, and semiprone. The authors prefer the prone position on a radiolucent rotating Jackson operative table. A Wilson frame may be used as an alternative. The arms are extended cephalad in cases involving lower thoracic levels. In cases involving higher thoracic levels, we prefer to carefully tuck the arms at the sides with adequate padding and protection. This allows more room for the operating surgeon; however, one must make sure that this does not obstruct intraoperative radiographs. General endotracheal anesthesia is used with some surgeons preferring a double-lumen catheter. All bony prominences are well padded and protected to prevent unwanted neurovascular compression.

Somatosensory and motor evoked potential monitoring is obtained at baseline prior to positioning, postpositioning, and throughout the operative procedure. Mean arterial pressures are maintained at or above 80 mm Hg throughout the entire procedure.

The position of the incision is dependent on whether instrumentation is used, the extent of exposure required, or often the surgeon's preference. Multiple incision types have been described: midline, paramedian, hockey stick, and semilunar (▶ Fig. 26.2). The patient is draped wide and lateral over the rib cage to ensure complete access.

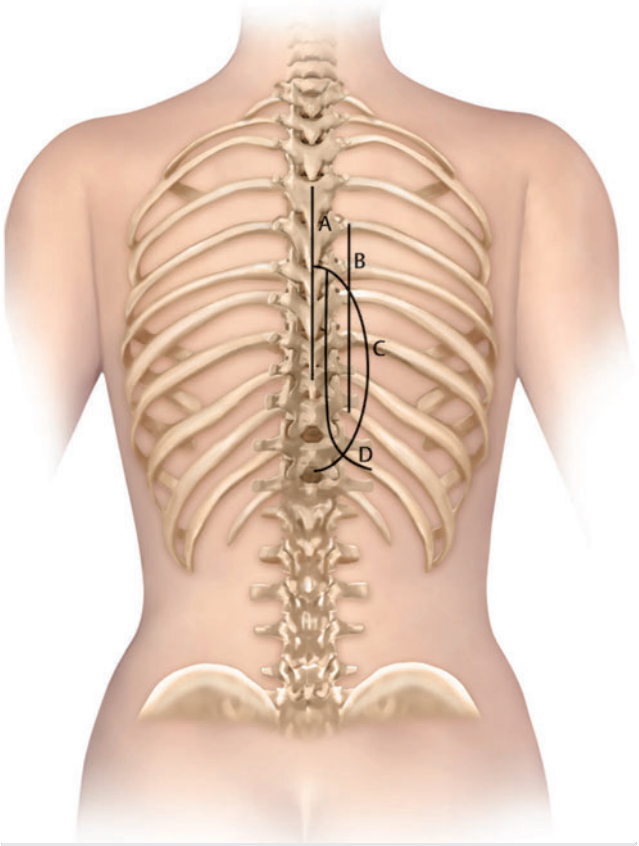

Fig. 26.3 Various incisions utilized.

26.8 Tips, Pearls, and Lessons Learned

The length and number of ribs will often depend on the access requirements. Generally, 2 to 5 cm of rib at two levels will allow for adequate access to two vertebral levels (▶ Fig. 26.3). In cases requiring more extensive debulking or en bloc resection, a greater number of ribs or greater length of resection may be required. In cases where exposure is limited, the use of angled mirrors or an endoscope may substantially improve visualization. When accessing a disk space, the rib below the level of

interest must be exposed (the seventh rib must be exposed to access the T6–T7 disk space). The rib is dissected subperiosteally and medially to the level of the vertebral articulation. This will lead to the cephalad disk space. A trough can be created within the vertebral body. This acts as a cavity to push the herniated disk contents into the cavity avoiding manipulation of the spinal cord. In a case that requires a single complete or partial rib head resection, no instability is created; therefore, no instrumentation is required. In cases that require two or more ribs to be removed, posterior instrumentation is recommended.

To gain adequate access for decompression or reconstruction, nerve root sacrifice is often necessary. Patients must be warned about the clinical sequelae that may result. When performing lateral foraminal or vertebral dissection, radicular arteries are often encountered and are often sacrificed. These feeder vessels may contribute critically to the blood supply of the spinal cord and must be considered before sacrifice due to the potential for cord ischemia. Remember the variable location of the artery of Adamkiewicz (most commonly, left-sided T10–T12). A preoperative angiogram is sometimes advocated.

26.9 Difficulties Encountered

Intraoperative localization can be very difficult and requires adequate preoperative localizing radiographs. We prefer a full-length scout sagittal computed tomography (CT) or magnetic resonance imaging (MRI). Intraoperatively, the levels are counted using live fluoroscopy from the sacrum in a cephalad direction to the level of interest. If there is concern about using this method, preoperative marking by an interventional radiologist may be helpful.

Careful subperiosteal dissection of the rib, vertebra, and articulation is necessary to avoid inadvertent pleural violation or segmental artery injury. In many pathologic processes such as a tumor or infection, there is often significant pleural scarring that makes pleural violation unavoidable. If a violation of the parietal pleura is encountered, we advocate primary closure with absorbable suture. A Valsalva maneuver can be performed to confirm closure. The pleural repair can be augmented with a Gelfoam (Pfizer Pharmaceuticals) sponge. A chest tube can be placed postoperatively if determined necessary. A postoperative chest radiograph is recommended to check for pneumothorax in cases where a pleural violation was not identified intraoperatively.

Bleeding may be encountered at multiple steps during the surgery. To avoid inadvertent bleeding from the intercostal vasculature, the rib is carefully dissected subperiosteally; the vessels are identified and properly ligated. Excessive bleeding may be encountered during the vertebral body resection. Hemostatic agents such as bone wax, Gelfoam, FloSeal (Baxter Healthcare), or SURGICEL (Johnson & Johnson) may assist in controlling this loss. An autogenous blood recovery system can be utilized in indicated cases (noninfectious or neoplastic). If it cannot, multiple units of cross-matched blood should be available.

Because of the indirect visual access to the anterior thecal sac, durotomy with cerebrospinal fluid (CSF) leak may be encountered. The dura should be repaired primarily if possible. Because of the technical difficulty of repairing anterior durotomies, a repair with a layered dural substitute (e.g., DuraGen, Integra Life Sciences) and sealant (e.g., DuraSeal, Covidien; TISSEEL, Baxter Healthcare) may be necessary. In cases where a dural tear is encountered and a chest tube is required, the chest tube should not be placed on suction to avoid brainstem herniation.

When exposing higher thoracic levels, the scapula may obstruct the necessary lateral exposure. In these cases, the scapula must be retracted laterally after the rhomboid and trapezius muscles are divided and retracted medially.

Spinal cord injury is a catastrophic complication that results from inadvertent manipulation of the spinal cord or vascular compromise. In cases where multiple ribs are removed and significant portions of the vertebral body are resected, instrumentation should temporarily be placed cranial and caudal to the levels of resection to avoid instability and cord manipulation.

26.10 Key Procedural Steps (Video 26.1)

A midline approach is utilized extending one to two levels cephalad and caudal to the level of interest. Dissection is carried out subperiosteally to the level of the transverse process and rib. Electrocautery is used to transversely divide the paraspinal musculature at the level of the ribs. Careful attention to avoid intercostal penetration must be maintained by frequent digital palpation during the dissection. Generally, 5 cm of rib are exposed laterally and subperiosteally using a Doyen periosteal elevator or Penfield no. 1. The neurovascular bundle on the undersurface of the rib is retracted inferiorly and ligated as necessary. A Hibbs retractor can assist with this lateral exposure.

If it is known that the exposure will destabilize the segments of interest, pedicle screw fixation at the cranial and caudal levels is performed at this juncture. Temporary rod fixation is placed contralateral to the side of the costotransversectomy to avoid iatrogenic movements that may cause injury to the spinal cord.

If indicated based on a preoperative assessment, a wide laminectomy may be performed. This may help identify the boundaries of the spinal canal including the pedicles and neural foramina. The transverse process is subsequently removed with a Leksell rongeur and the costovertebral articulation is further skeletonized using electrocautery. The costotransverse ligaments are identified and transected by carefully advancing a Cobb elevator into the joint space. The rib (previously subperiosteally exposed) is divided laterally using a rib cutter. The anterior pleura are bluntly dissected from the rib and lateral vertebral body using periosteal elevators. The rib is carefully disarticulated using Kerrison rongeurs. The subperiosteal dissection from the vertebral body is first carried out at the level of the pedicle to avoid the segmental vasculature as well as the exiting nerve root (▶ Fig. 26.4). The exiting nerve is identified medially to the level of the neural foramina and protected throughout. A malleable retractor may further assist in the anterior displacement and protection of the pleura while further subperiosteal dissection may expose most of the vertebral body and cephalad anulus.

In the setting of significant disk-level pathology, the posterolateral anulus is identified and incised. The superior and inferior endplates at the level of disk compression are burred to

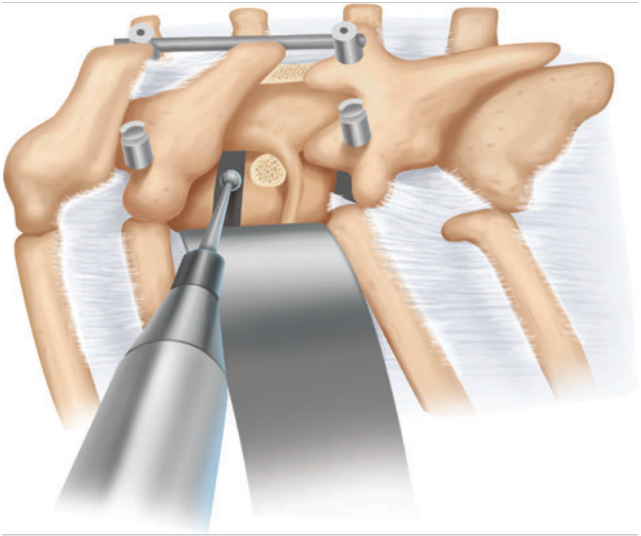

Fig. 26.4 The cranial and caudal disk levels are adequately visualized.

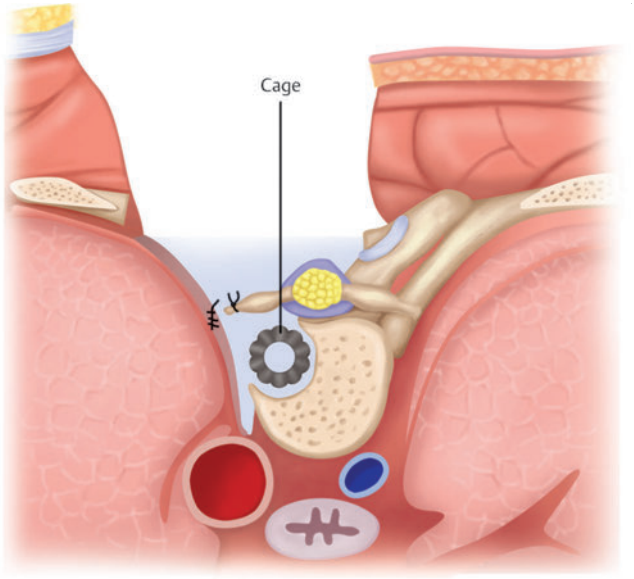

Fig. 26.5 Cross section after cage placement.

create a cavity to displace the herniated disk contents. An Epstein curette is used to apply a ventral directed force against the disk contents into the previously created endplate troughs. At no point should any force be directed at the level of the spinal cord.

Vertebral body resection is carried out carefully and briskly to avoid significant blood loss. A combination of osteotomes and a bur are used to complete the vertebrectomy.

In cases when extensive vertebral debridement is needed or if an intervertebral graft is going to be placed, an additional rib or two may require resection. Bilateral costotransversectomies may be required to safely position a large intervertebral graft (▶ Fig. 26.5). Nerve root sacrifice is often necessary and should be performed lateral to the neural foramina. Silk ties are applied proximal and distal to the level of transection.

At the completion of the procedure, the wound is copiously irrigated and a Valsalva maneuver is performed to detect an occult pleural violation, if discovered and irreparable, a chest tube is placed during the procedure or immediately postoperatively.

26.11 Bailout, Rescue, and Salvage Procedures

- Inadequate exposure is a commonly encountered problem. The approach may be expanded by extending the incision, removing multiple ribs, or converting to an extracavitary procedure allowing for greater pleural retraction.
- When exposure necessitates destabilization of the spinal column, posterior spinal instrumentation is necessary.
- In cases that require extensive vertebral column resection, an anterior fusion will be necessary. In these circumstances, an anterior cage is favored to provide the greatest stability.
- When heavy and diffuse bleeding is encountered, hemostatic agents are utilized to control bleeding. If the bleeding remains uncontrolled, the wound should be packed and closed.
- If intraoperative spinal cord monitoring detects a spinal cord injury, thorough circumferential decompression should be performed to ensure no compressive pathology exists. Mean arterial blood pressures should be maintained at greater than 85 mm Hg. A wake-up test as well as the initiation of spinal cord injury steroid protocols should also be considered.

Pitfalls

- Spinal cord injury
- Incidental durotomy
- Wrong-level surgery
- Postoperative pneumothorax
- Unplanned instability
- Uncontrolled bleeding

27 Lateral Extracavitary Approach

Howard B. Levene, George M. Ghobrial, and Jack Jallo

27.1 Description

The lateral extracavitary approach has been developed to approach the posterior lateral and anterior lateral aspects of the spine and dura without the need for an anterior thoracic or abdominal exposure. The approach allows the surgeon to manipulate instruments with decreased retraction on the dura, as well as to avoid pressure on the spinal cord when utilized rostral to the thoracolumbar junction. The lateral extracavitary approach was originally developed for Pott's disease, but has gained considerable use today and been proven effective for diskectomy, vertebrectomy, biopsy, and fusion.

27.2 Expectations

This approach affords the spine surgeon visualization of the posterolateral and anterolateral vertebral body. If a corpectomy is performed, the surgeon can visualize the posterolateral and anterolateral dural surfaces. The surgeon can perform a diskectomy, vertebrectomy, biopsy, or fusion with instrumentation through one incision. If posterior instrumentation (i.e., thoracic pedicle screws) is desired, the incision allows the additional placement of instrumentation. The surgical approach can be technically challenging. The procedure requires expertise, experience, and a comfortable knowledge of thoracic and retroperitoneal anatomy.

27.3 Indications

A lateral extracavitary approach is indicated for anterolateral dural compression. Compression may arise from trauma, neoplasm, infection, or degenerative changes. The approach is ideal when an anterolateral decompression is necessary to perform a vertebrectomy, diskectomy, biopsy, and/or fusion.

27.4 Contraindications

Patients who have had thoracic or pulmonary trauma or cardiopulmonary limitations may not be good candidates for any type of surgical intervention. Patients with severe abnormalities of the rib cage or spine (e.g., severe scoliosis) are less than ideal candidates for an extracavitary approach.

27.5 Special Considerations

Exposure at the limits of the approach (T1–T5 and L5–S1) is difficult. For lower lumbar exposures, protection of the lumbar nerves within the iliopsoas muscle is required. The artery of Adamkiewicz, the largest radicular segmental vessel, has an unpredictable origin, although its violation should not be an afterthought. It arises from the left side of the aorta in three-quarters of patients between T8 and L1, and injury to this vessel can result in a spinal cord infarct. Preoperative spinal angiography may be considered. Approaching the spine from the contralateral side to the artery of Adamkiewicz may be desirable. The fascia of the middle to lower thoracolumbar spine forms an aponeurosis, which when incised to expose the erector spinae muscle, often creates a large potential space. The space must be closed meticulously to prevent seroma formation. For exposure of a single vertebra, the ribs above and below must be excised.

27.6 Special Instructions, Positioning, and Anesthesia

The operating table may be angled to provide better visualization. It is important, therefore, to make sure the patient is well secured to allow rotation. When nerve roots are encountered, gentle retraction using vessel loops is useful. Tracing intercostal nerves/arteries back to the dura will identify the pedicles above and below the entrance to the foramen. Neuroelectrophysiology (somatosensory evoked potentials, motor evoked potentials) monitoring is highly advisable as an early-warning method for neural irritation. When planning for anterior grafting when a decompression is not necessary, it is advisable to leave the posterior cortex intact, if possible, to protect the dura. Close consultation with the anesthesiologist is required. Some authors have recommended single-lumen intubation with high-frequency ventilation. Prior to closure, fill the wound with saline to inspect for a pneumothorax or air leaks.

27.7 Tips, Pearls, and Lessons Learned

The approach has limits depending on the level of the spine. The confines of the upper thoracic spine include the narrowing of the thoracic inlet, and the presence of great vessels, mediastinum, and lung apices. At the middle to low thoracic spine, the diaphragm is an impeding anatomical structure. Anatomical constraints in the lumbar spine include the abdominal viscera, kidneys, and great vessels. Unique anatomical challenges of the lumbosacral junction include the narrow pelvic inlet and the iliac vessels. During dissection, ligating the intercostal nerves distally allows better access to the foramen. Ligating the intercostal nerves creates a tolerable band of hypesthesia and avoids a dysesthetic pain syndrome from stretch injuries. Some difficulties inherent in the procedure include persistent bleeding, which may require fresh frozen plasma if there is greater than 2 L of blood loss.

27.8 Key Procedural Steps

The anesthesiologist must be alerted to the possibility of lung intubation. Central intravenous (IV) access or large-bore IV access and an arterial line are recommended. For nononcologic cases, Cell Saver (Haemonetics) is recommended. The patient may be positioned on chest rolls and secured tightly. The

ipsilateral chest roll can be placed medially to allow the scapula to fall away for high thoracic approaches. Depending on the levels to be approached, consider a Mayfield pin frame versus face pad support, often when the cervicothoracic junction or more rostral segments need to be stabilized. Create a midline, or in some practices, a curvilinear hockey-stick skin incision three segments above and below the target level for a corpectomy and fusion. For a diskectomy, only 1.5 segments above and below the target level are required for adequate exposure. Alternatively, a paramedian linear incision can be used for exposure. In this case, the incision can be extended to the lateral crest for bone harvesting. However, with knowledge of the prefascial planes, the iliac crest can be harvested from a lumbar midline incision without the need for a second incision. A lateral, parallel fascial incision will be made over the iliac crest and should be closed after hemostasis from the graft site is achieved. The typical midline exposure should allow for visualization of the spinous processes, laminae, and transverse processes; this is achieved by extending the rostrocaudal incision as needed. There will be aponeurotic attachments at the transverse process. Dissect laterally to find the lateral margin of erector spinae muscles and retract the superficial soft tissues medially. For exposure up to C7, identify and separate the fascial planes of the trapezius and rhomboids and reflect them laterally as a myocutaneous flap. For exposure of the lateral thoracic or thoracolumbar junction, rib removal is required frequently at and below the vertebral level of interest. The rib may be dissected in its entirety (subperiosteal circumferentially) or dissected as a vascularized bone graft with preservation of the neurovascular bundle. During dissection, identify nerves and tag them with vessel loops. Intercostal nerves may be sacrificed proximal to the dorsal root ganglion for exposure (▶ Fig. 27.1). Extra caution should be taken when the indication is infection or infiltrative malignancy, as the inflammation can make the process of achieving a safe plane of dissection difficult, increasing the risk of pleural violation.

Dissect the lateral pedicle and vertebral body taking care to preserve the pleura. A high-speed drill or a rongeur is used to remove the pedicle. For a diskectomy, a combination of pituitary rongeurs and curettes are used. At some practices, a modified Gigli saw is used. A Woodson tool can be used to palpate the anterior surface of the anulus to confirm adequate disk removal.

For a corpectomy, proceed with a high-speed drill to remove the anterior portion of the vertebral body. Take care to leave a thin rind of bone anteriorly, laterally, and posteriorly. Remove the posterior cortex at the conclusion of the decompressive procedure. Continue bone resection to the contralateral pedicle. At the conclusion of the dissection, break the posterior vertebral margins to decompress the neural elements. It is important to note that with the dura mater exposed, manipulation of compressive lesions by instrument maneuvers away from the dura is advocated. Wound drains are regularly placed.

27.9 Difficulties Encountered

For soft tissue bleeding, cauterize and pack as necessary. For damage to the great vessels, an emergent vascular surgery consult is recommended. When compressing/packing bleeding tissue, take care to avoid compressing the dura. If the bleeding is uncontrollable, the wound can be packed and closed, and a separate approach can be performed at a later time. If a pneumothorax or hemothorax is suspected, a chest tube should be placed.

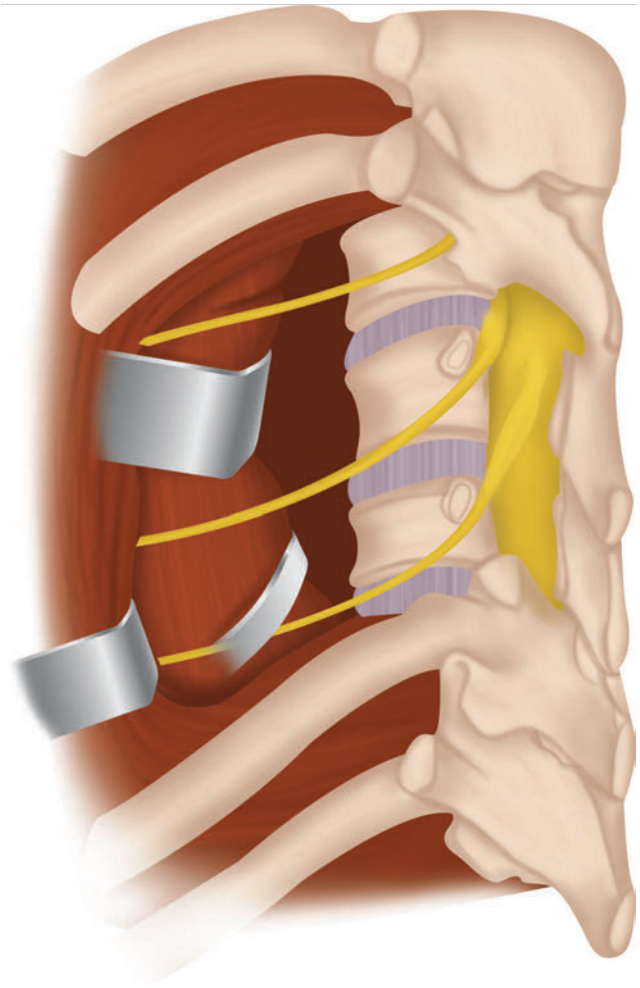

Fig. 27.1 Lateral view of the retracted paraspinal muscle bundle medially and the myocutaneous flap laterally, the lateral dural sac and exiting nerve roots, and the lateral vertebrae.

27.10 Key Principles

- The lateral extracavitary procedure is a highly useful procedure due to its large, wide exposure allowing for visualization of the posterolateral and anterolateral vertebral body. With a corpectomy, the surgeon can visualize the posterolateral and anterolateral dural surfaces, also allowing for a diskectomy, vertebrectomy, biopsy, or fusion with instrumentation through one incision.
- With increased surgical time and complexity comes the increased risk for complications. Proper patient positioning is key for prolonged exposures: A successful surgery can be undermined by improper patient positioning.
- In expert hands, this procedure allows for maximal decompression of the spinal cord and neural elements from anterior pathologies from a posterolateral corridor.

27.11 Bailout, Rescue, and Salvage Procedures

This exposure requires an experienced understanding of the regional anatomy. Careful review of the regional anatomy is the best practice to avoid the need for salvage. In the setting of infiltrative malignancy, the risk of pleural violation is elevated and may require the aid of thoracotomy tube placement to assist with treatment of a pneumothorax or monitor postoperative bleeding into the pleural space.

Pitfalls

- This approach requires extensive knowledge of thoracolumbar anatomy. The great vessels are close to the operative field and there is a danger of excessive bleeding. Any dural tears encountered should be primarily repaired. Consider cerebrospinal fluid (CSF) drainage if needed. Beware of the potential of iatrogenic neurologic injury to the cord and nerve roots. Incomplete decompression is a risk. Violating the pleura may result in a pneumothorax or hemothorax. Be aware of the possibility of postoperative ileus.
- This operation is not recommended for patients with severe cardiac or pulmonary disease, or a life expectancy of less than 3 months. For patients who refuse blood or blood products, one should reconsider this approach.

Section VI

Posterior Thoracic Arthrodesis and Instrumentation

28 Supralaminar, Infralaminar, and Transverse Process Hook Placement *94*

29 Sublaminar Fixation *97*

30 Thoracic Pedicle Screw Placement: Anatomical, Straightforward, and In-Out-In Techniques *101*

VI

28 Supralaminar, Infralaminar, and Transverse Process Hook Placement

Steven C. Ludwig and Alexander R. Vaccaro

28.1 Description

The safe placement of hooks within the thoracic spine allows for surgical correction and stabilization of a variety of spinal disorders. Anchor-site selections include a downgoing supralaminar hook, upgoing infralaminar hook, and either an up- or more commonly downgoing transverse process hook.

28.2 Key Principles

Spinal instrumentation systems are characterized by a rod (longitudinal component) that is segmentally fixed to the spine via a hook or screw (anchor).

28.3 Expectations

Three-dimensional corrective forces may be delivered to the spine for deformity correction, graft compression, or spinal stabilization. Despite the merits of segmental fixation, careful attention must be directed toward the preparation of a fusion bed because all rigid implant systems will fail if a solid fusion is not achieved.

28.4 Indications

- Scoliotic and paralytic deformity
- All types of spinal instability including trauma, degenerative, neoplastic, and congenital
- Laminar hooks may help shield pedicle screws and prevent late screw failure.

28.5 Contraindications

- Severe osteoporosis
- The absence of posterior elements
- Active posterior infection

28.6 Special Considerations

Careful preoperative planning is essential to determine the site of hook placement. Paired hooks in an apposing claw configuration provide a secure fixation point, especially at the ends of a construct.

28.7 Special Instructions, Positioning, and Anesthesia

The patient should be placed in a prone position; a variety of frame choices include the Relton-Hall frame, Wilson frame, or Jackson table. Consider controlled intraoperative hypotension in the absence of significant cord compression and electrophysiology monitoring.

28.8 Tips, Pearls, and Lessons Learned

Preoperative and intraoperative communication with the surgical staff concerning the levels and types of hook facilitates the placement of the instrumentation.

28.9 Difficulties Encountered

An alternative method of segmental fixation or a change in the instrumented level should be performed if violation of the lamina or transverse process makes hook placement unsafe.

28.10 Key Procedural Steps

Thoracic laminar hooks can be placed against the superior or inferior edge of the lamina. Laminotomy windows are performed, using a skinny-nose Leksell rongeur. Depending on the level, the interspinous/ supraspinous ligaments are taken down to expose the ligamentum flavum. At the extremes of instrumentation placement, the supraspinous and interspinous ligaments should be preserved. Also, one may place hooks on each side of the spine without removing the interspinous ligaments. Following removal of the interspinous ligaments, the ligamentum flavum is removed until epidural fat is visualized. Using a 2-mm Kerrison, the laminotomy site is widened laterally. One or two millimeters of the superior facet may be removed to allow for proper hook seating (▶ Fig. 28.1). Care is taken to bite away only the ligamentum flavum and preserve the epidural fat to avoid epidural bleeding. A trial laminar hook is grasped with a hook holder and placed into the space created. Infralaminar hooks can be directly placed under the lamina in an upgoing fashion (▶ Fig. 28.2). The blade of a supralaminar hook should be inserted by rotation about the arc of the hook to facilitate the placement and minimize spinal canal hook intrusion (▶ Fig. 28.3). Hook purchase is checked manually with a gentle posteroanterior maneuver.

Downward- or upward-facing transverse process hooks are inserted over the superior or inferior edge of the transverse process, respectively. The edge of the transverse process is cleared in a subperiosteal fashion using electrocautery. A curved transverse process hook starter is used to enter the region along the anterior aspect of the transverse process, into a small triangular space bounded anteriorly by the rib head and laterally by the costotransverse process articulation (▶ Fig. 28.4). A trial transverse process hook is placed into space and hook purchase and is checked manually with a gentle posteroanterior maneuver.

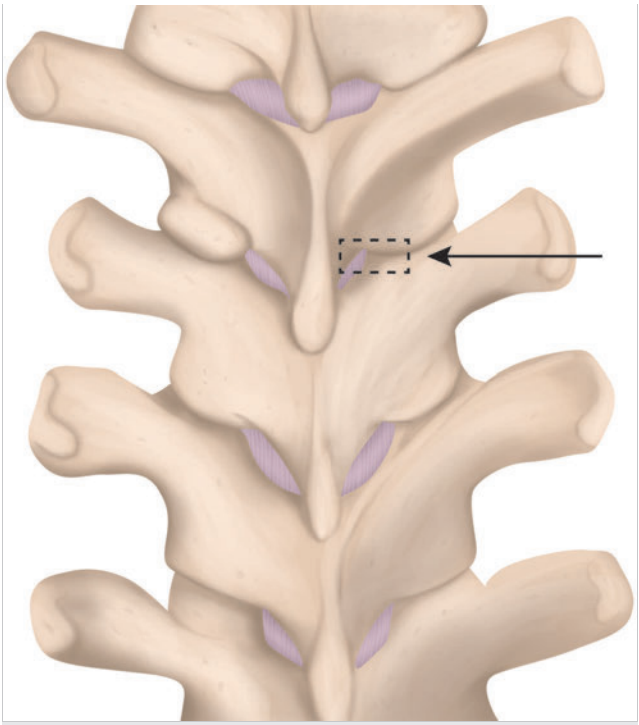

Fig. 28.1 A supralaminar hook requires a small intralaminar laminotomy. A small medial facetectomy may also be required to allow for hook seating.

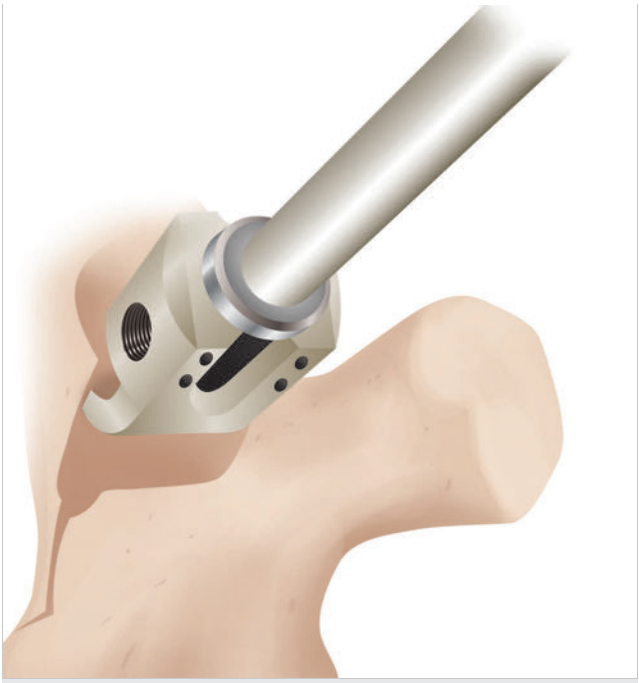

Fig. 28.2 Placement of an infralaminar hook with gentle upward positioning.

28.11 Bailout, Rescue, and Salvage Procedures

Alternative methods of fixation include the use of pedicular or cortical screw fixation when the anatomical morphometry of the pedicles make this technique a viable option. The upward-facing hook option may allow for the placement of a pedicle hook instead of an infralaminar hook. The addition of a pedicular-screw hook is available as an additional means of fixation. Be aware that placement of pedicle hooks is frequently not possible at the lower thoracic levels because of a more sagittal facet orientation. Transverse process screws directed bicortically

Fig. 28.3 Supralaminar hook placement.

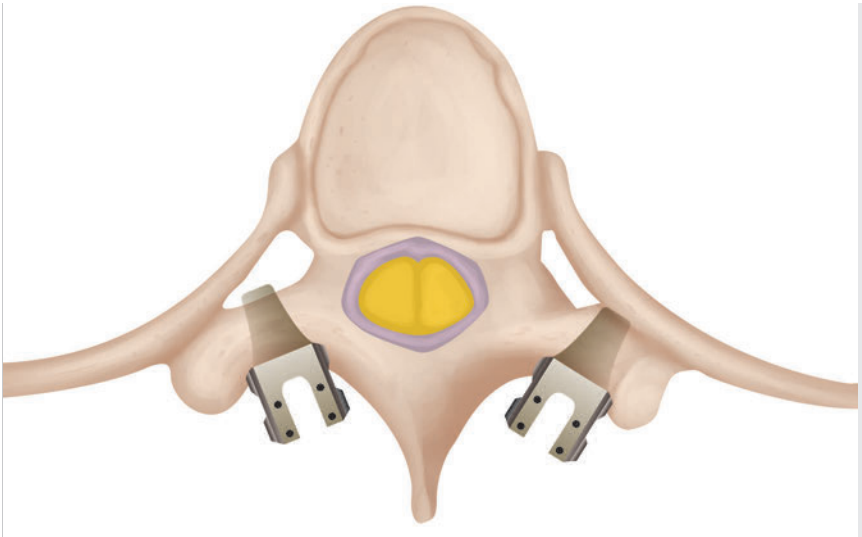

Fig. 28.4 Appropriate position of a thoracic transverse process hook.

through the transverse process and into the rib head may be a good alternative method of fixation if the type of instrumentation allows for this option.

Pitfalls

- Avoid placing two laminar hooks at the same levels to prevent iatrogenic spinal canal stenosis from hook placement.
- Beware of fracturing the transverse process and losing a segmental point of fixation by creating an intraosseous defect with the transverse process hook starter.
- Transverse process hook placement may not be possible in the lower thoracic spine because the transverse processes become smaller in size and more vertically oriented.
- Rotation of a supralaminar hook into the spinal canal prevents the risk of forcing the hook into the spinal canal.
- When creating the laminotomy sites, epidural bleeders can be controlled with the use of a bipolar, FloSeal (Baxter Healthcare), or a thrombin-soaked Gelfoam (Pfizer Pharmaceuticals) patty.

29 Sublaminar Fixation

Michael J. Vives, Sanjeev Sabharwal, and Neel Shah

29.1 Description

Sublaminar wires or bands are often used in conjunction with longitudinal members (rods) to provide rigid segment stability to the posterior spine. Such sublaminar fixation devices are an efficient means of manipulating the spinal column in both the coronal and sagittal planes.

29.2 Key Principles

The risk of bone/implant failure with this type of construct can be lessened by utilizing multiple points of fixation. Supplemental wire placement at the extremes of the instrumentation construct resists implant pullout in the sagittal plane. Individual wires or bands of the construct can be gradually and repeatedly tensioned to gradually effect a reduction without compromising the bone–implant interface.

29.3 Expectations

Sublaminar implant placement is extremely safe in well-trained hands. Substantial translational correction in the coronal plane is possible in relatively flexible coronal or sagittal plane (especially lordotic) deformities (▶ Fig. 29.1). A recent study demonstrated similar operating times for scoliosis cases using apical sublaminar wires versus pedicle screws.

29.4 Indications

Any multilevel posterior fusion construct with intact posterior elements.

29.5 Contraindications

Sublaminar fixation devices should not be placed in regions of spinal stenosis, swelling of the neural elements, or levels of posterior element fracture or deficiency. Physical contact of dissimilar metals should be avoided due to the risk of accelerated corrosion. Stainless steel wires should not be used in conjunction with titanium rods.

29.6 Special Considerations

Once a well-contoured sublaminar wire is passed, it should be twisted over the respective posterior lamina to prevent inadvertent canal migration. More recently, polyester sublaminar bands have been developed. The flat surface of the band distributes contact forces over a wider surface area. This should decrease the risk of cutting through the lamina during tensioning and reduction maneuvers. As the bands are rigidly affixed to the rods by clamps, such constructs are more axially stable than their wire-rod counterparts. They are more costly, however, so some surgeons may utilize bands at strategic points

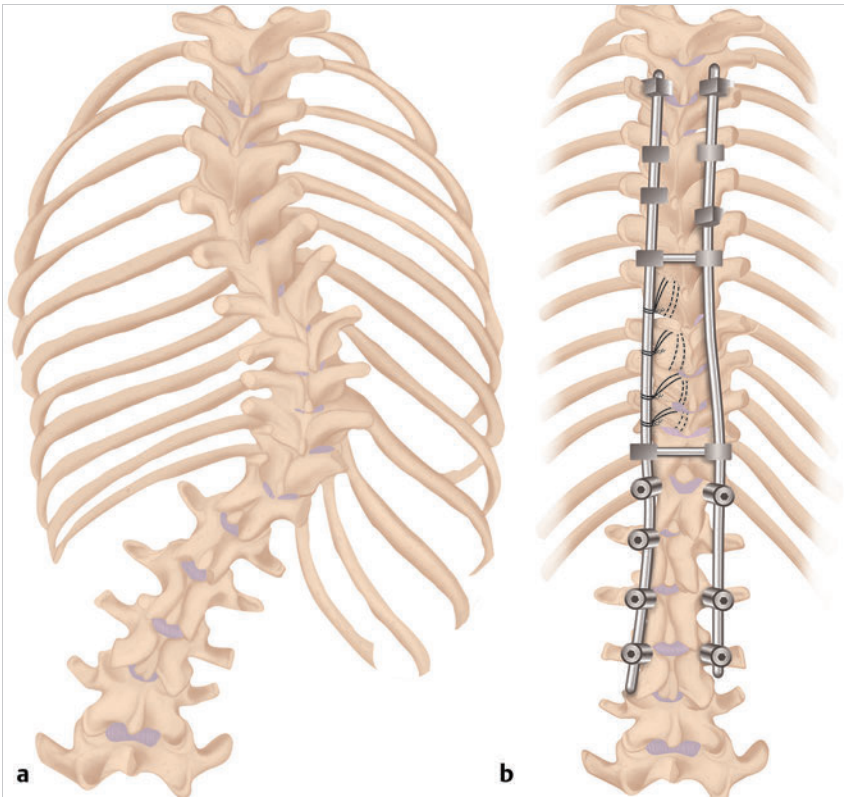

Fig. 29.1 (a, b) A patient with scoliosis treated with posterior instrumentation and fusion using apical sublaminar wires.

(such as the concavity of the major curve) and wires in less critical segments of the construct.

29.7 Special Instructions, Positioning, and Anesthesia

The radius of curvature of the bent sublaminar wire should be at least equal to the width of the lamina. The primary bend can be made over the handle of a Cobb elevator, with a compensatory bend to facilitate wire passage. The wires should be passed just beneath the lamina in a caudal to cranial direction. Central passage of the wires under the lamina avoids the potential for nerve root injury from lateral wire deviation and minimizes the risk of encountering epidural bleeders. The spinous processes of the instrumented vertebrae are removed with a double-action bone cutter to adequately visualize the ligamentum flavum. A narrow Leksell rongeur is used to create a midline defect in the ligamentum flavum, which is further enlarged with Kerrison rongeurs to allow safe passage of the sublaminar wire.

29.8 Tips, Pearls, and Lessons Learned

Develop a routine for wire passage where the inferior tail of the sublaminar wire is placed either medial or lateral to the superior tail at the time of wire bending, prior to twist-locking the wire ends. Some favor placing the inferior tail laterally because the free ends of the wire can puncture the surgeon's gloves. Remember always to separate the wire ends at the time of rod placement prior to wire tightening to avoid the technical difficulty of trying to slip a wire end between the rod and bone after the wire is well seated. When twist locking the wire ends, rotate the wire ends clockwise away from the midline. If wires are placed at levels above or below the instrumentation, they should be twist-tightened in a direction away from the fusion mass. For long constructs utilizing sublaminar wires as the primary fixation, wiring alternate levels instead of every level does not compromise the stability of the construct, provided that the most proximal two levels are consecutively wired. This practice would theoretically decrease the risk of cord injury and reduce surgical time.

29.9 Difficulties Encountered

The potential for neurologic compromise is low in sublaminar wire placement. At any point during passage of the wires, if there is any resistance at all, the wire should be removed, repositioned, possibly recontoured, and then gently reinserted. Forceful insertion of sublaminar wires may result in inadvertent thecal sac compression. If there is excessive epidural bleeding, gentle tamponade with Gelfoam (Pfizer Pharmaceuticals) or use of bipolar electrocautery can be utilized. When many wires are utilized, it can be difficult to keep track of which set of wire ends correspond to which lamina. Placing a hemostat on the wire ends at every other level can help ensure that the corresponding ends of each wire are twist-locked around the rod at the time of rod placement.

29.10 Key Procedural Steps

Expose the ligamentum flavum at the levels of anticipated wire placement. A midline defect is created with a narrow Leksell rongeur and carefully widened with a Kerrison. Luque double-bent wires or doubled 16- or 18-gauge wires are prebent at one end into a semicircular arc. To avoid inadvertent jolting and canal penetration, the sublaminar wires are usually the last bony anchors that are inserted just before performing corrective maneuvers for spinal deformities. The wires are passed in four steps: introduction, advancement, roll-through, and pull-through. The wire should be introduced at the midline of the inferior edge of the lamina. The tip of the wire should remain in contact with the undersurface of the lamina as it is advanced cranially (▶ Fig. 29.2). The wire should be rolled so the tip emerges at the upper end of the lamina in the midline. The looped leading edge can then be grasped with a nerve hook or narrow needle holder. The wire is then pulled through by keeping a firm posterior force on the leading and trailing edge of the wire (▶ Fig. 29.3). The wire ends are then bent to conform to the posterior lamina as described above (▶ Fig. 29.4). At the time of rod placement, the wire ends are separated to allow the rod to rest between them. The wires are then tightened by twisting in a clockwise direction using a jet wire twister (▶ Fig. 29.5). Retightening of the wires is often necessary before they are shortened with a wire cutter. The twisted wire ends are then twist-folded in the direction of wire twisting toward the midline posterior elements (▶ Fig. 29.6).

The technique for utilizing sublaminar polyester bands is similar to that described above for wires (see **Video 29.1**). The

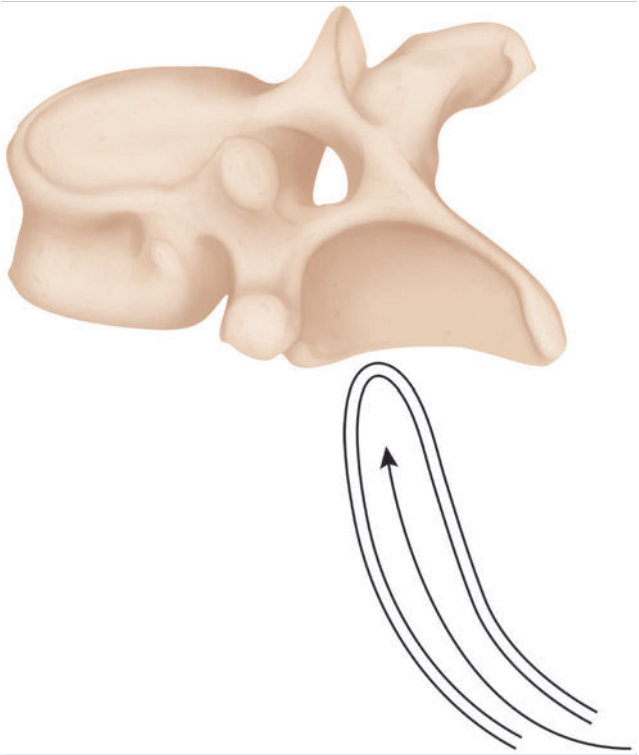

Fig. 29.2 The tip of the wire should remain in contact with the undersurface of the lamina as it is advanced cranially.

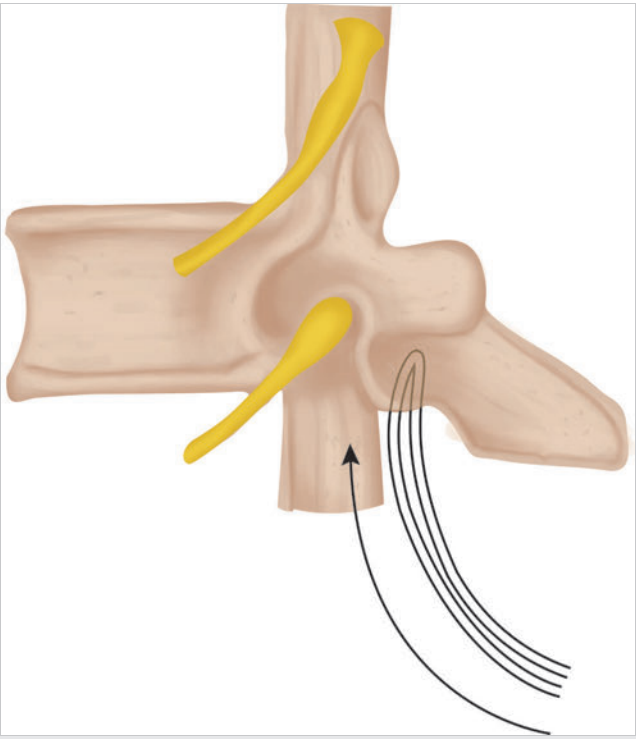

Fig. 29.3 Lateral view of the wire being advanced through the spinal canal.

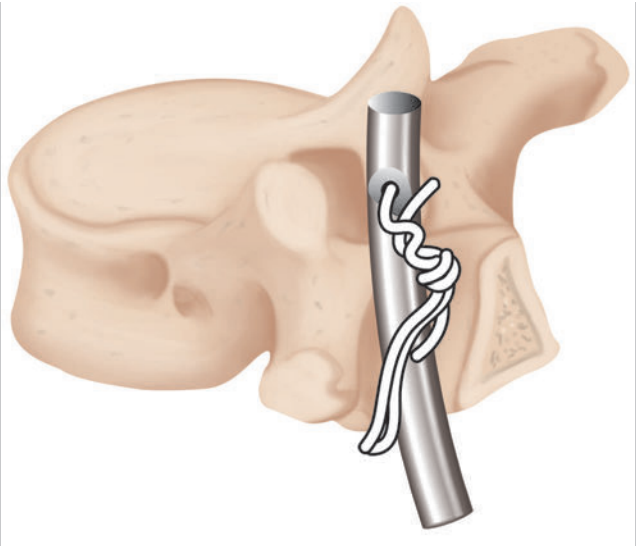

Fig. 29.6 The twisted portion of the wire is then twist-folded in the direction of the wire toward the midline posterior elements.

insertion and retrieval sites are prepared in a similar fashion. Creation of a slightly larger defect in the ligamentum flavum will permit easier passage and retrieval of the flexible leader of the band. The leader is bent to a similar configuration as a wire, and can be advanced freehand beneath the caudal edge of the lamina. After passing beneath the lamina, the leader can be visualized as it emerges cephalad to the superior edge. We have found that a no. 2 Kerrison is helpful to grasp the flat leading

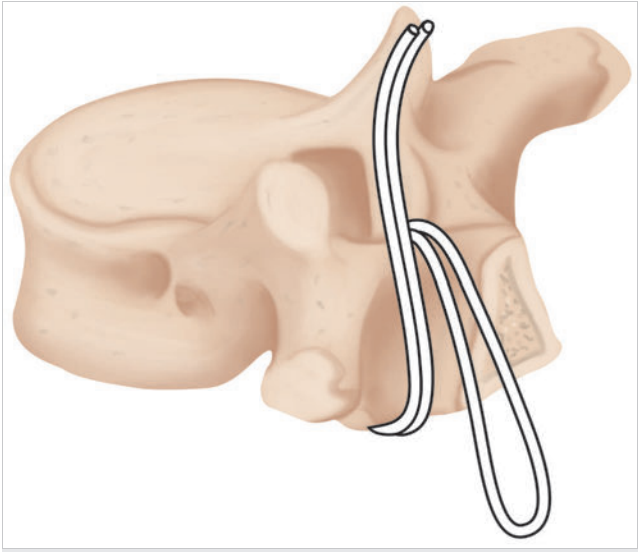

Fig. 29.4 The wire ends are bent to conform to the posterior laminae.

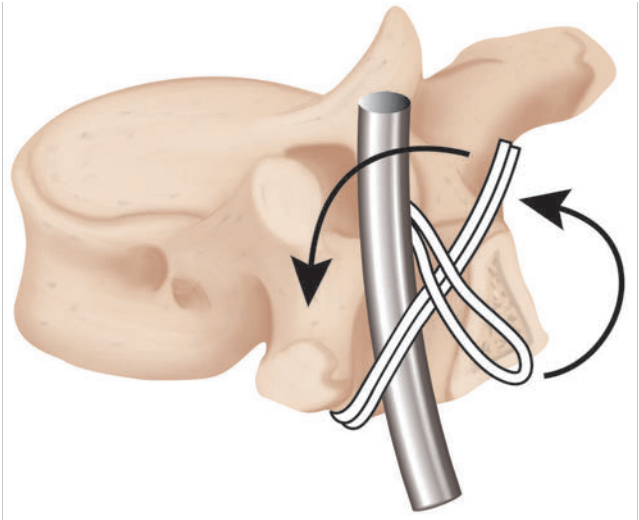

Fig. 29.5 Wires are tightened around the rod.

edge. The band is then pulled through, keeping firm posteriorly directed force on both the trailing and leading ends. The ends of each band are then provisionally passed through a clamp that will later be rigidly attached to the rod after all of the sublaminar implants have been placed. At the time of rod implantation, the clamps are provisionally attached to the rod and gradual tensioning of the band is done with a calibrated reduction tool. A set screw is tightened to maintain the final tensioning of the band and rigidly attach the clamp to the rod.

29.11 Bailout, Rescue, and Salvage Procedures

If a sublaminar implant cannot be placed without undue effort, it should be removed and passage should be reattempted after evaluating the passage route for evidence of obstruction. All

sublaminar devices should be removed if there is any evidence of sustained electrophysiologic or neurologic decline or weakness during a Stagnara wake-up test. If bony failure results at the time of wire tightening, an alternate level of spinal fixation should be chosen or transpedicular fixation, if applicable, can be performed.

Pitfalls

- Neurologic injury (spinal cord, nerve root) is the most common reported complication caused by the passing of the sublaminar wires.
- The most common reported symptom is temporary hyperesthesia caused by nerve root trauma.
- An infrequent complication is bony failure via wire pull-through, especially in the osteopenic patient.
- An adequate laminotomy is required to facilitate wire passage; however, the size should be limited to prevent compromise of the mechanical strength of the lamina.
- Overzealous tightening of the wire can also lead to wire breakage.

30 Thoracic Pedicle Screw Placement: Anatomical, Straightforward, and In-Out-In Techniques

Jason Ferrel, Thai Trinh, and David Hannallah

30.1 Description

Pedicle screw instrumentation of the thoracic spine is used to provide stability through bony purchase until fusion occurs. The advantages of pedicle screw fixation in the thoracic spine over traditional laminar hook constructs include improved rigidity, resistance to axial pullout, improved deformity correction, avoidance of hardware within the spinal canal, and lack of reliance on facet or laminar bone quality.

30.2 Key Principles

Successful pedicle screw instrumentation must obtain and sustain adequate bony purchase to provide stability until bony fusion occurs. Improved pedicle screw pullout strength correlates with increased bone mineral density, tapping prior to screw insertion, increased screw placement depth, fully threaded screws, increased screw diameter, higher insertional torque, and bicortical screws. Screws inserted in areas with the most robust dorsal cortex have improved torque on insertion and increased pullout force. Although commonly used, polyaxial screws have a reduced bending yield strength compared to monoaxial screw designs.

Traditionally, three different screw paths are used for thoracic pedicle screw placement. In the anatomical technique, the screw can be directed along the pedicle axis. In the straightforward technique, the screw is directed perpendicular to the plane of the posterior vertebral body and parallel to the midline of the vertebral body. In the in-out-in technique, the screws are directed through the transverse process and back into the pedicle. Typically, it is possible to achieve a longer screw with the anatomical technique because the depth to the anterior cortex along the pedicle axis is longer than along a line parallel to the midline of the vertebral body. However, screws placed using the straightforward technique gain purchase in the denser subchondral bone and have a higher pullout strength and maximal insertional torque than with the anatomical technique. Although bicortical screw placement may provide a biomechanically superior construct, it is not without risk of significant disastrous complications in the thoracic spine.

30.3 Expectations

Thoracic pedicle screw placement is a technically demanding procedure and carries significant neurovascular risks. The learning curve for placement of thoracic pedicle screws using the free-hand technique is approximately 60 screws.

30.4 Indications

Thoracic pedicle screws are used to provide stability through bony purchase until fusion in the setting of fractures, dislocations, infections, scoliosis, kyphotic deformities, and degenerative disease.

30.5 Contraindications

- Too narrow pedicle (medial to lateral) to accept screw
- Inability to confidently identify pedicle
- Inadequate bone stock for screw purchase

30.6 Special Considerations

The starting point and screw trajectory during thoracic pedicle screw placement can be determined using the freehand technique or using intraoperative imaging. Screw placement has been demonstrated to be safe using either the freehand technique or with fluoroscopic guidance. Navigation systems based on preoperative imaging may improve accuracy of placement and reduce cortical breaches.

Thoracic pedicle width is narrowest from T4–T8, and screw fixation at these levels may not be safe. Careful review of pedicle width on preoperative computed tomography (CT) is warranted. The distance from the medial pedicle wall to the dural sac ranges from 0.0 to 1.4 mm and the distance of the exiting nerve roots to the inferior pedicle wall range from 0.8 to 6.0 mm. When using the trajectory of the anatomical technique, there is a larger effective pedicle diameter in the sagittal and axial planes, and the maximal insertional arc in the sagittal plane is larger (vs. the straightforward technique).

30.7 Special Instructions, Positioning, and Anesthesia

General anesthesia is required. The patient is positioned in the prone position on a radiolucent table. A standard posterior approach to the thoracic spine is performed. Intraoperative neuromonitoring may provide early warning of a potential neurologic event. Intraoperative imaging including plain radiographs, multiplanar fluoroscopy, three-dimensional fluoroscopy, and CT-based assisted navigational systems, is used by some surgeons.

30.8 Tips, Pearls, and Lessons learned

- Many different anatomical landmarks have been suggested for determining a pedicle screw starting point.
- A careful review of preoperative imaging to determine each patient's unique pedicle morphology is essential.
- Preoperative imaging identifies pedicles that are too small to accept screws.

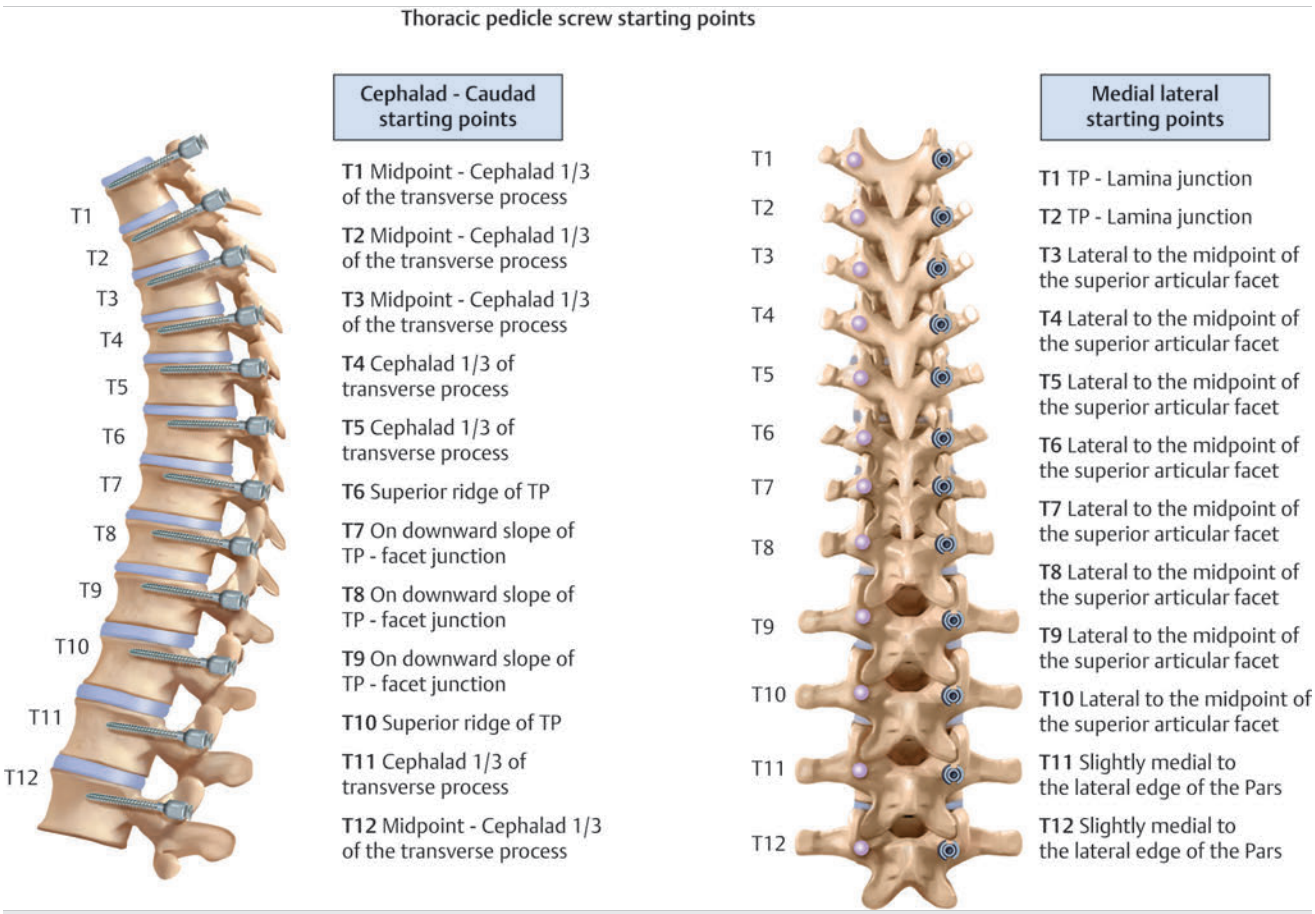
Thoracic pedicle screw starting points
Cephalad - Caudad starting points
T1 Midpoint - Cephalad 1/3 of the transverse process
T2 Midpoint - Cephalad 1/3 of the transverse process
T3 Midpoint - Cephalad 1/3 of the transverse process
T4 Cephalad 1/3 of transverse process
T5 Cephalad 1/3 of transverse process
T6 Superior ridge of TP
T7 On downward slope of TP - facet junction
T8 On downward slope of TP - facet junction
T9 On downward slope of TP - facet junction
T10 Superior ridge of TP
T11 Cephalad 1/3 of transverse process
T12 Midpoint - Cephalad 1/3 of the transverse process
Medial lateral starting points
T1 TP - Lamina junction
T2 TP - Lamina junction
T3 Lateral to the midpoint of the superior articular facet
T4 Lateral to the midpoint of the superior articular facet
T5 Lateral to the midpoint of the superior articular facet
T6 Lateral to the midpoint of the superior articular facet
T7 Lateral to the midpoint of the superior articular facet
T8 Lateral to the midpoint of the superior articular facet
T9 Lateral to the midpoint of the superior articular facet
T10 Lateral to the midpoint of the superior articular facet
T11 Slightly medial to the lateral edge of the Pars
T12 Slightly medial to the lateral edge of the Pars
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
T12

Fig. 30.1 Chart showing starting points and trajectory for thoracic pedicle screws. TP, Transverse Process

- Burring the prominent transverse process can improve pedicle screw trajectory and screw seating.
- Using the open lamina or mini-laminotomy techniques may reduce the rate of pedicle violation. This may be especially useful at the apex on the concave side of a curve, where the cord is closest to the pedicles.

30.9 Difficulties Encountered

- The gear shift should "fall" into the pedicle with steady, minimal resistance. Any sudden change in resistance to the gearshift probe should raise concern for cortical perforation and requires investigation.
- Cortical perforation during screw placement poses a risk to surrounding neurovascular structures. Most pedicle wall fractures occur through the thinner lateral wall of the pedicle. However, neurologic deficit is not common in instances of cortical perforation. In the upper thoracic spine, the trachea and esophagus are at risk with right- and left-sided pedicle screws that penetrate the anterior cortex, respectively.
- Hardware failure can occur including screw breakage, loosening, or pullout.

30.10 Key Procedural Steps

A meticulous exposure of the posterior elements involves subperiosteal dissection of the facet joints to expose the lateral border of the superior articular process, the tips of the transverse processes, and removal of soft tissue from the facet joints. Several methods for identifying the correct starting points based on anatomical landmarks for the anatomical and straightforward techniques have been described. A general guide for starting points is provided in ▶ Fig. 30.1. Regardless of the technique being used, a very careful evaluation of pedicle morphology on preoperative CT is critical to surgical planning and avoiding neurovascular injury.

In the anatomical technique, the correct trajectory is established as the pedicle is probed with a gearshift directed along a path perpendicular to the dorsal cortical surface of the facet and parallel to the pedicle axis (approximately 20 degrees in craniocaudal direction). In the straightforward technique, the pedicle is probed with a gearshift directed parallel to the superior endplate of the vertebral body in a straightforward direction. In the in-out-in technique, the starting point is the cephalad and lateral-most aspect of the tip of the transverse process. The trajectory passes through the costovertebral joint and terminates within the vertebral body.

A cutting bur is used to make a small breach of the posterior cortex at the appropriate starting point for the particular thoracic level, and a blush of bleeding cancellous bone will be appreciated. Ventral pressure is applied to the gearshift, with the curve facing laterally, until reaching the neurocentral junction, a depth of approximately 20 mm. A ball-tip feeler is used to ensure that no pedicle breach has occurred. The gearshift is reinserted, with the curve now facing medially, and advanced to its final depth. A ball-tip feeler is again used to confirm the integrity of the bony tunnel on five cortices. Alternatively, a straight awl may be used. A tap is performed with a diameter of 1 mm less than for the intended screw. The screw is placed and intraoperative fluoroscopy/radiography confirms appropriate intraosseous position of the screw (**Video 30.1**).

30.11 Bailout, Rescue, and Salvage Procedures

- Using longer or larger diameter screws
- Using a different screw trajectory for the revision screw
- Extending the instrumentation construct an additional vertebral level
- Augmentation of failed screw holes with cement or bone graft
- Pediculolaminar hooks and translaminar screw placement are additional options for fixation.
- Using the open lamina or mini-laminotomy techniques may reduce the rate of pedicle violation.

Pitfalls

- Preoperative imaging reveals pedicles are too small to accept screws.
- Poor bone stock or screws with inadequate fixation require revision.
- Cortical penetration has been associated with neurovascular and visceral injury.
- A large retrospective review of 4,790 screws reported a screw penetration rate of 5.1%, a 1% nerve root irritation rate, and 1% screw breakage rate.

Section VII

Anterior Thoracic Decompression

31 Open Transthoracic Diskectomy *106*

32 Open Thoracic Corpectomy via the Transthoracic Approach *109*

VII

31 Open Transthoracic Diskectomy

Grant D. Shifflett, Russel C. Huang, Jennifer Shue, and Patrick F. O'Leary

31.1 Description

Open transthoracic diskectomy is performed to decompress symptomatic thoracic herniated nucleus pulposus (HNP) in patients with myelopathy or myeloradiculopathy.

31.2 Key Principles

The clinical manifestations of thoracic disk herniations are not always apparently related to the thoracic spine and can therefore present a diagnostic challenge. Moreover, the reported radiographic prevalence of thoracic herniated disks in asymptomatic individuals is 37%. Thus, radiographic findings must be well correlated with the history and physical examination findings before recommending surgery. Neural compression may result in myelopathy or radiculopathy. Myelopathy may manifest as motor, sensory, or reflex changes distal to the level of compression, gait disturbance, or bowel/bladder dysfunction. Radiculopathy may result in pain or sensory changes in a dermatomal distribution. The differential diagnosis includes cervical or lumbar stenosis, herpes zoster, infections or neoplasms, central nervous system disorders, and systemic or peripheral neuropathies. Thoracic axial pain from disk disease should be treated nonsurgically in most cases.

Due to the high incidence of paraplegia following laminectomy for the treatment of central thoracic HNP, a variety of surgical approaches have been developed. However, transthoracic decompression remains the gold standard for the treatment of symptomatic central thoracic disk herniations because it offers superior visualization of the disk and dura in the central zone of the spinal canal and minimizes iatrogenic cord manipulation and compression.

31.3 Expectations

Surgery is performed to prevent progressive neurologic injury from ongoing cord compression. Despite adequate decompression, pre-existing neurologic deficits may not resolve. Thoracic axial pain may not improve. The risk of postoperative paralysis is significantly higher than the risk of paralysis after cervical or lumbar decompressive surgery.

31.4 Indications

- Absolute: Myelopathy with progressive neurologic deficits
- Relative: Painful radiculopathy from a thoracic HNP not amenable to posterior decompression

31.5 Contraindications

- Pulmonary disease
- Prior thoracic surgery prohibiting a safe thoracotomy

31.6 Special Considerations

In addition to standard imaging, it is useful to obtain a continuous computed tomography (CT) or magnetic resonance imaging (MRI) scan that includes the entire thoracic and lumbosacral spine. The scans should be correlated with full-spine plain films and scrutinized for supernumerary vertebrae, rib abnormalities, or lumbosacral transitional anomalies that might generate confusion in the intraoperative identification of levels.

Measure the mediolateral width of the vertebral body at the level of the ventral floor of the spinal canal using CT or MRI. Knowing this width is helpful in ensuring that the mediolateral extent of disk removal is adequate.

31.7 Special Instructions, Positioning, and Anesthesia

- We recommend intraoperative neural monitoring.
- A beanbag is useful to maintain true lateral decubitus positioning intraoperatively.
- Maintaining the patient in a true lateral position keeps the surgeon oriented to the spinal canal and spinal cord.
- The rib, as the embryologic equivalent of the lumbar transverse process, leads to the identically numbered pedicle (e.g., 10th rib to T10 pedicle).
- Hypotensive anesthesia is not desirable. Blood pressure should be maintained normo- to hypertensive to maintain cord perfusion.
- Single- or double-lumen endotracheal intubation can be considered depending on operative levels.

31.8 Tips, Pearls, and Lessons Learned

- Preoperative measurement of the width of the vertebral body is helpful in determining how "deep" to go with the bur to reach the other side of the spinal canal (right side of the canal in a left-sided approach).
- Beware of the asymptomatic disk.
- Carefully scrutinize fluoroscopy and correlate with digital palpation to avoid wrong-level surgery.

31.9 Difficulties Encountered

Extensive calcification of the disk appears to raise the risk of intraoperative dural tears and must be handled carefully.

31.10 Key Procedural Steps

The patient is placed in the lateral decubitus position (**Video 31.1**). Above T6 a right-sided approach is preferred to avoid the heart and aortic arch. Below T6, left-sided approaches are

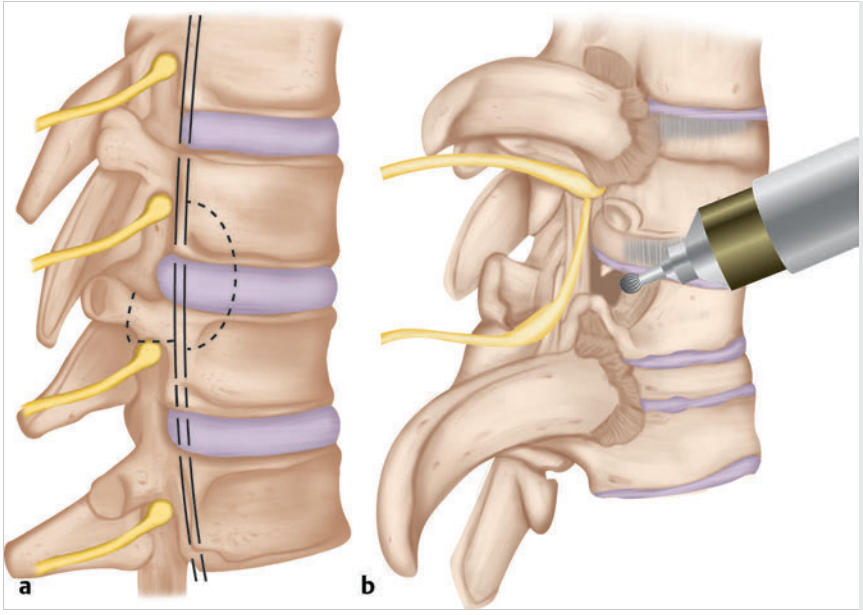

Fig. 31.1 Thinning of the caudal pedicle with a bur. (**b**) Resection of the pedicle reveals the lateral aspect of the dural tube, the ventral floor of the spinal canal, and the disk itself.

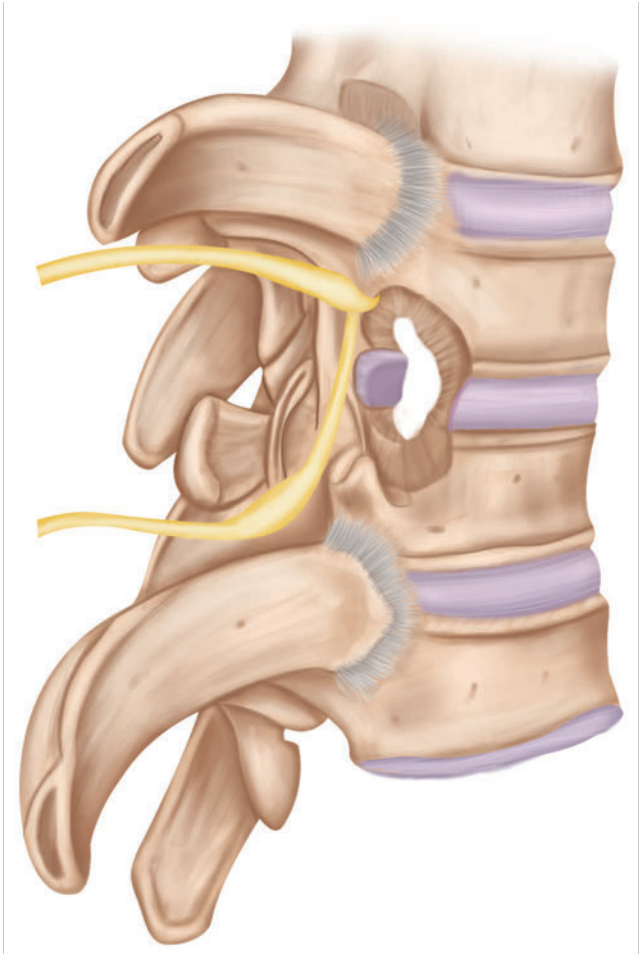

Fig. 31.2 Partial corpectomy of cephalad and caudal vertebrae is performed, leaving a thin shell of posterior bone and disk in contact with the dura.

preferred because the aorta is relatively safer to handle and mobilize. A break in the table may be considered for lower levels (i.e., T11–T12), but is not always necessary. The chest is usually entered one or two rib levels above the disk of interest due to the natural anatomical tilt of the rib cage. Intraoperative fluoroscopy can be used to identify the ideal location for the incision. After entering the chest cavity, exposure of the ipsilateral lung to the atmospheric pressure generally allows for adequate deflation of the lung and sufficient visualization can be obtained with gentle retraction. However, in the upper thoracic levels a double-lumen endotracheal tube can be utilized to deflate the ipsilateral lung if more exposure is needed. Preliminary identification of levels may be aided by intrathoracic palpation of the first rib and counting distally. Intraoperative radiographs are taken to confirm levels. The correct level can be identified by visualizing the 12th rib and corresponding vertebral body on anteroposterior radiographs, or by counting up from the sacrum on lateral radiographs.

Once the appropriate level has been identified, the rib head overlying the disk and caudal pedicle is resected. The neurovascular bundle caudal to the rib should be identified and protected. If necessary, the segmental artery should be ligated as distant from the foramen as possible to best preserve cord perfusion. The cephalad segmental artery should be preserved if possible to maximize cord perfusion. Following rib head removal, dissecting and tracing the neurovascular bundle medially leads to the foramen, the pedicle, and the lateral margin of the disk and vertebral bodies.

The caudad pedicle is thinned with a bur and resected with a Kerrison rongeur, revealing the lateral aspect of the dural tube (ventral margin) of the spinal canal, and the disk itself (▶ Fig. 31.1). Do not attempt to place any instruments between the disk and the cord at this time. A bur is used to perform partial corpectomies above and below the affected disk, leaving undisturbed the posterior shell of bone and disk material that is in direct contact with the dura (▶ Fig. 31.2).

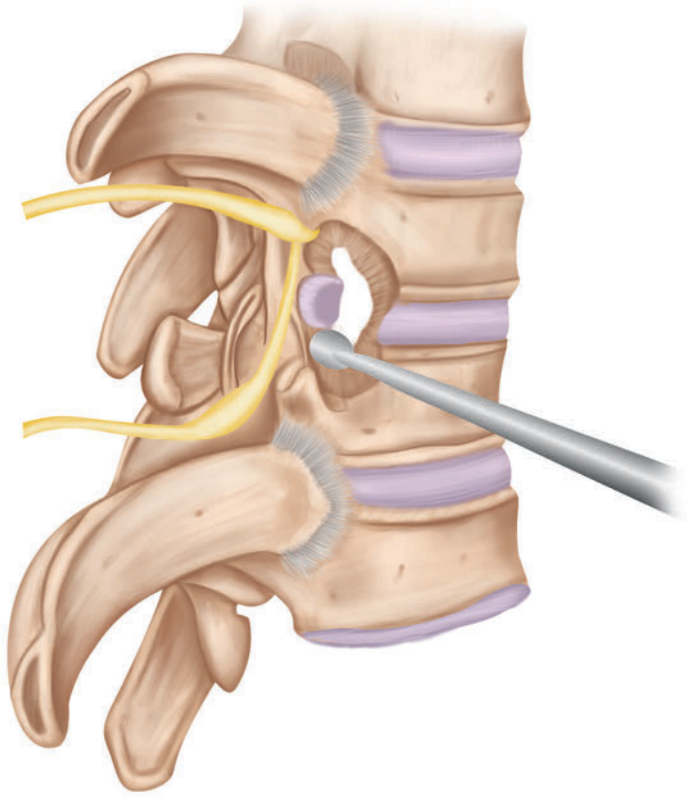

Fig. 31.3 Curettes are used to push the thin posterior shell of bone and disk away from the spinal cord.

Having created a void in the vertebral body anterior to the offending disk, the thin posterior shell of bone and the disk are pushed away from the cord using small curettes (▶ Fig. 31.3). Unnecessary contact with the dura and spinal cord, particularly near the zone of maximal compression, is avoided.

The need for fusion and instrumentation remains controversial. Fusion is more likely to be needed if destabilizing bone resection is performed, or if the disk is at the thoracolumbar junction. Fusion may be performed using rib and corpectomy autograft with or without cages, anterior, and/or posterior instrumentation. A thoracolumbar orthosis may help promote fusion.

Suture closure of the thoracotomy defect using drill holes through the inferior rib may reduce postoperative intercostal neuralgia (note: avoid drill holes in superior rib as this risks injury to the associated neurovascular bundle). A chest tube is used postoperatively.

31.11 Bailout, Rescue, and Salvage Procedures

Irreparable dural tears may be partially sealed with fibrin glue or similar dural sealants. Placing a lumbar subarachnoid drain may be useful.

Pitfalls

- Neurologic deterioration
- Wrong-level surgery
- Intercostal neuralgia
- Vascular injury
- Pulmonary morbidity
- Dural tears

32 Open Thoracic Corpectomy via the Transthoracic Approach

James D. Kang and Mustafa H. Khan

32.1 Description

Access to the anterior thoracic spine via the transthoracic approach (via thoracotomy) can be used for decompression and fusion.

32.2 Key Principles

To perform adequate decompression and stabilization of the thoracic spine, obtaining good exposure is a must. Preservation and protection of the vascular structures in the thoracic cavity is the key to such an exposure.

32.3 Expectations

- To obtain exposure of the targeted thoracic spine safely
- To protect the vascular/visceral structures of the thoracic cavity
- To decompress (with or without fusion) the involved thoracic spine levels adequately

32.4 Indications

- Burst fractures with canal compromise and neurologic deficit
- Large extruded thoracic disks with cord compression
- Intraspinal tumors
- Infections

32.5 Contraindications

- Severe pulmonary disease
- Medical comorbidities (e.g., severe cardiac disease)
- Concurrent/potential posterior spinal instability

32.6 Special Considerations

Preoperative workup should include imaging modalities (plain radiographs, magnetic resonance imaging [MRI]/computed tomography [CT] scan) to specifically define the area of decompression. If a tumor is being evaluated, CT angiography and embolization are helpful in preoperative planning. Assistance by a thoracic surgeon for exposure is highly recommended.

32.7 Special Instructions, Positioning, and Anesthesia

Intraoperative somatosensory- or motor- evoked potentials should be used to monitor spinal cord function. The patient is placed in a lateral decubitus position with the operative side (right or left, depending on the thoracic level) up (▶ Fig. 32.1). Flexing the table allows the intercostal space to open up slightly, which aids in exposure. Magnifying loupes and headlights are quite helpful. Using a double-lumen endotracheal tube to deflate one lung can aid in improving visualization. Placement of a nasogastric tube is helpful in identifying the esophagus intraoperatively.

32.8 Tips, Pearls, and Lessons Learned

A left-sided approach is generally preferred for most thoracic levels (with the exceptions noted below). The level of entry between ribs depends on level of pathology; as a general rule it is better to err cephalad than caudad due to the rib anatomy. Access to T2 and T3 vertebral bodies via thoracic corpectomy is technically challenging—a sternal splitting approach may be easier. The other option is a very high periscapular thoracotomy, performed via excision of the fourth rib. Finally, a right-sided approach to T11–L1 may place the liver at risk; therefore, great caution needs to be exercised.

32.9 Difficulties Encountered

Ligation of segmental vessels is useful for maintaining good hemostasis. On the left side, the artery of Adamkiewicz is at risk

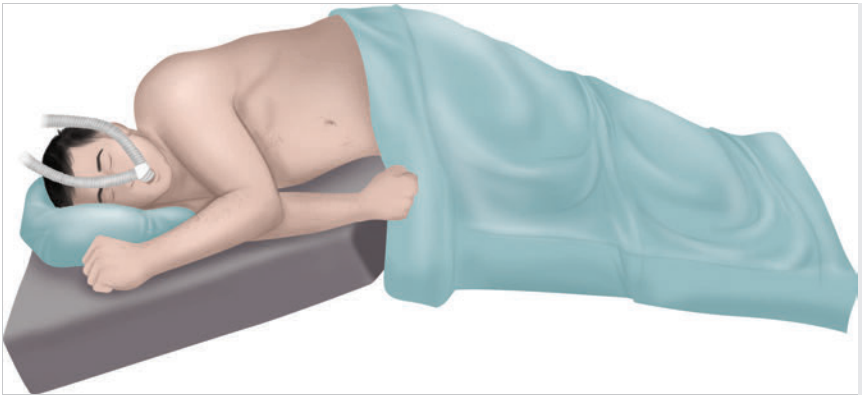

Fig. 32.1 The patient is positioned in a lateral decubitus position.

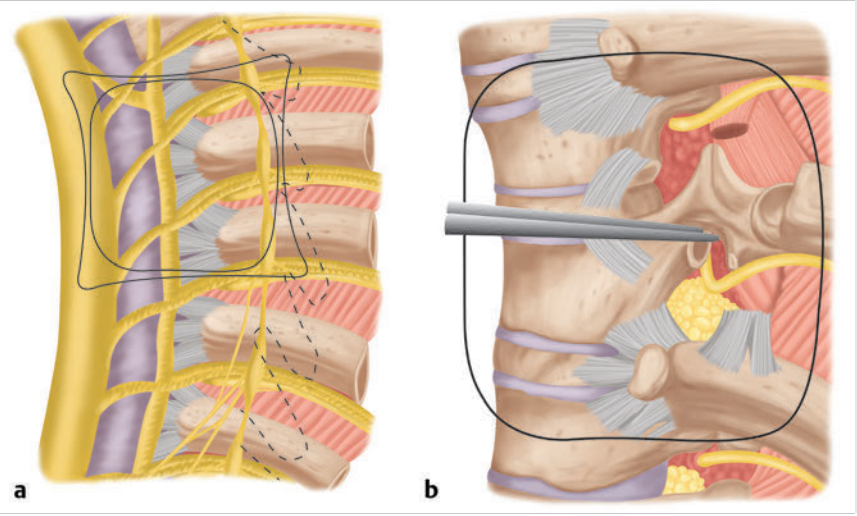

Fig. 32.2 (a, b) A window is made through the parietal pleura over the vertebral body.

between T9–T12. One may temporarily clamp the segmental vessels and then observe for any neuromonitoring signal changes. However, it should be remembered that the blood supply to the spine via segmental vessels can be highly variable. Also, entering into the wrong interspace and having to work cephalad through the exposure increases surgical difficulty. During left-sided approaches, the thoracic duct is at risk for injury. The aorta and inferior vena cava are almost always visible in the surgical field. The hemiazygous and azygous systems are vulnerable to injury especially high in the thoracic spine. This is important because placement of anterior instrumentation under the aorta may lead to late aortic erosion and catastrophic aortic rupture. Some patients (especially those with severe lung disease) cannot tolerate unilateral lung deflation. Care must be taken to not puncture visceral pleura. The use of a bur during a corpectomy should be performed with great caution for obvious reasons. Finally, inadequate decompression of the vertebral bodies may result if decompression is not carried all the way to the far pedicle.

32.10 Key Procedural Steps

A thoracotomy incision is made at the level corresponding to the vertebral level to which access is being sought. In large or obese patients, it may be difficult to identify the appropriate intercostal rib space to enter. Intraoperative plain radiographs with a spinal needle can help with the identification of the levels, but in general, it is better to err on the more cephalad level because it is technically easier to perform the corpectomy working cephalad to caudal rather than vice versa. Care is taken to perform the dissection of the rib on its superior border to avoid damage to the intercostal nerve and vessels that run along the inferior border. The dissection is carried down into the thoracic cavity by incising the pleura. A self-retaining rib-spreader is placed between the cephalad and caudad ribs. It is often necessary to resect the rib to allow for better retraction; otherwise, it is not uncommon to fracture the ribs with the rib-spreading retractors. The lung is deflated via the double-lumen tube. Within the chest cavity, the rib that corresponds to the vertebral body that will be removed with the corpectomy is followed posteriorly to the spine, where it articulates at the cranial border of the vertebral body and the intervertebral disk (e.g., the eighth rib articulates into the T7–T8 disk space). It is strongly advisable at this time to obtain a confirmatory plain radiograph with a spinal needle to check that the levels have been counted correctly. The parietal pleura are resected, making a rectangular window over the vertebral body and the rib heads (▶ Fig. 32.2). The segmental vessel is ligated to fully expose the lateral bony wall of the vertebral body that is to be removed. The sympathetic chain is often encountered and should be ligated to enhance full exposure of the vertebral body and the adjacent disks. The rib head is now disarticulated to allow for exposure of the pedicle (the rib can be saved for use as bone graft). It is also important to remember that the rib head articulates with the transverse process (costotransverse articulation) as well as the vertebral body (costovertebral articulation), and that good exposure of the pedicle requires complete resection of these structures. Once this is done, the exiting intercostal nerve root can usually be visualized caudal to the pedicle. This anatomy allows the surgeon to clearly understand the posterior extent of the corpectomy (i.e., where the spinal canal begins) during the decompression phase of the operation. The pedicle is resected with a Kerrison rongeur, which allows for the exposure of the lateral border of the spinal canal (the lateral sleeve of the dura mater is now visualized along with the exiting nerve root). The cranial and the caudal disks are now resected with pituitary rongeurs. The vertebral body is then removed using a rongeur and a power bur (▶ Fig. 32.3). Unless a tumor is being resected, it is not necessary to resect the anterior cortex of the vertebral body, or the anterior longitudinal ligament. (These structures may provide a tension band during the reconstruction following the corpectomy and aid in keeping the bone graft encased within the corpectomy site.) The vertebral body should be burred toward the contralateral pedicle, and the posterior wall of the vertebral body adjacent to the spinal cord should not be removed until it is certain that the corpectomy trough has reached the contralateral pedicle. It is advisable to use a diamond-tip abrasive bur to undercut the posterior cortex at the contralateral pedicle, which will make the posterior wall of the vertebral body (fracture fragments or tumor that is compressing the spinal cord) "float." Once this has been achieved, curettes are used to

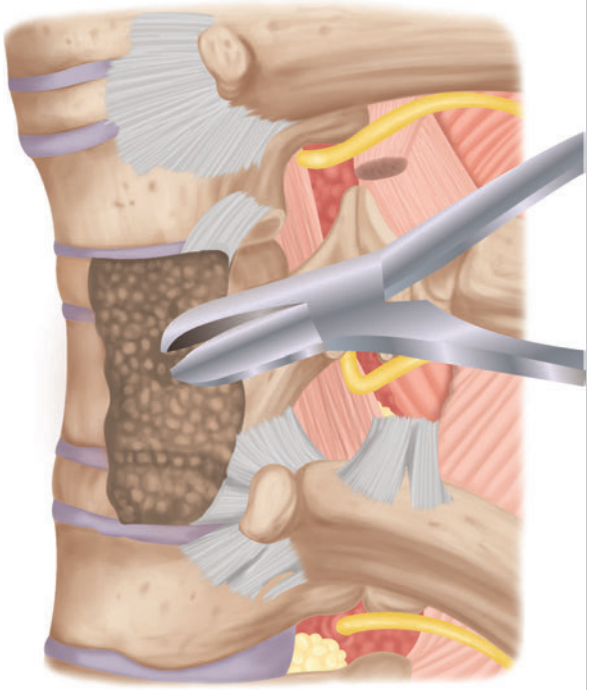

Fig. 32.3 The corpectomy is carried out all the way to the contralateral pedicle.

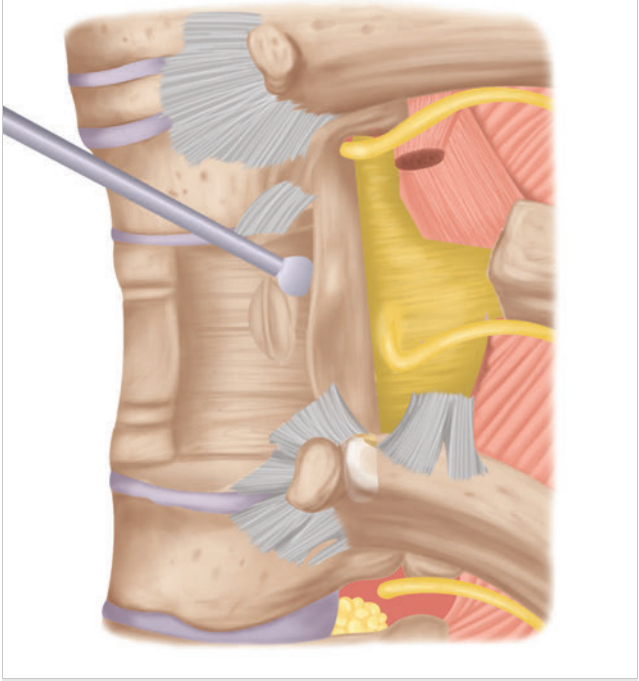

Fig. 32.4 The spinal cord is fully decompressed.

carefully pull the retropulsed bone fragments or tumor away from the spinal cord into the corpectomy trough. The posterior longitudinal ligament may be preserved or resected depending on the nature of the decompression that is being done (▶ Fig. 32.4). The contralateral pedicle is palpated with a Penfield elevator to ensure that a complete decompression has been achieved.

There are several choices for corpectomy reconstruction grafts. Tricortical iliac crest bone graft, humerus or femur allograft, and titanium metallic cage devices can all be used effectively with or without anterior instrumentation. We prefer using expandable cage devices in elderly patients with tumors, and structural allograft in the younger patients with traumatic injuries (▶ Fig. 32.5). Although anterior instrumentation is also available, we prefer using posterior stabilization to obtain a more stable circumferential arthrodesis.

The thoracotomy is closed over a chest tube, and postoperative chest radiographs are taken to ensure normal lung reinflation.

32.11 Bailout, Rescue, and Salvage Procedures

If for technical reasons the anterior procedure cannot be completed, then a posterior decompression and fusion strategy may be adopted instead. However, posterior surgery has limited usefulness because the spinal cord does not tolerate any retraction.

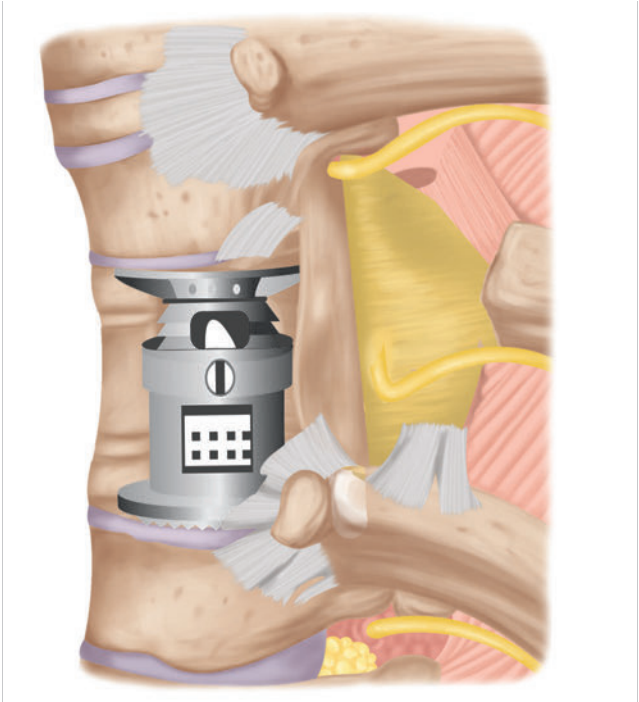

Fig. 32.5 An expandable cage is placed in the corpectomized vertebra.

Pitfalls

- If not properly ligated, segmental vessels can cause significant bleeding.
- Ligating more than two segmental vessels may compromise blood flow to the spinal cord.
- Bipolar electrocautery is useful in coagulating the small vessels. FloSeal (Covidien) is useful for augmenting hemostasis.
- The vena cava and aorta are at risk with this approach when decompression is being performed with a curette or Kerrison rongeur.
- If a double-lumen tube is used, the deflated lung should be inflated twice an hour to decrease the risk of postoperative atelectasis.
- Postoperatively close and aggressive pulmonary support is needed to minimize respiratory complications.

Section VIII

Anterior Thoracic Arthrodesis and Instrumentation

33 Anterior Thoracic Arthrodesis after Corpectomy (Expandable Cages, Metallic Mesh Cages) *114*

34 Anterior Thoracic and Thoracolumbar Plating Techniques *117*

VIII

33 Anterior Thoracic Arthrodesis after Corpectomy (Expandable Cages, Metallic Mesh Cages)

Michael C.L. Suryo, Sapan D. Gandhi, and D. Greg Anderson

33.1 Description

Various spine pathologies, such as fractures, destructive infections, and tumors, affect the vertebral body and lead to spinal instability. Surgical restoration of the anterior column, using metallic meshes or expandable cages, aims to decompress neural elements and provide biomechanical stabilization of the thoracolumbar spine following vertebrectomy.

33.2 Key Principles

The use of autogenous tricortical iliac bone graft for vertebral body replacement has been a standard technique for vertebral body replacement in the past. However, problems with this approach, including donor-site morbidities, pseudarthrosis, graft displacement, and graft collapse with kyphotic deformity have been reported. In recent years, a variety of surgical implants (cages) have been manufactured for vertebral body replacement in the thoracolumbar spine. First-generation cages for this purpose were made from titanium mesh or carbon fiber-reinforced polyetheretherketone (PEEK) materials. More recently, complex cage designs have proliferated, including some cages that are "expandable," allowing the surgeon to place the cage into the spinal defect and lengthen or expand the cage to fill the defect or eliminate residual kyphosis at the corpectomy site (▶ Fig. 33.1). Expandable cages offer several surgical advantages over nonexpandable metallic meshes: Expandable implants can be inserted at a small volume through minimally invasive incisions, and the adaptation of the implant configuration to the exact defect height is possible by in vivo extension of the device, thereby avoiding further trimming of the nonexpendable cages. In general, cages are designed to support bone in-growth or facilitate fusion across the corpectomy site.

33.3 Expectations

The use of a corpectomy cage is expected to reconstruct the anterior column of the thoracolumbar spine, restore normal alignment, provide stabilization, and achieve a solid fusion across the spinal defect. Clinically, this approach is designed to repair the spinal defect and provide a long-term stable solution to the underlying spinal disorder.

33.4 Indications

Vertebral body replacement is indicated in various pathologic conditions affecting the anterior column integrity, including certain fractures, tumors, destructive lesions, infections, and deformities.

33.5 Contraindications

Anterior column reconstruction should not be attempted as a primary or stand-alone treatment for severe spinal injuries

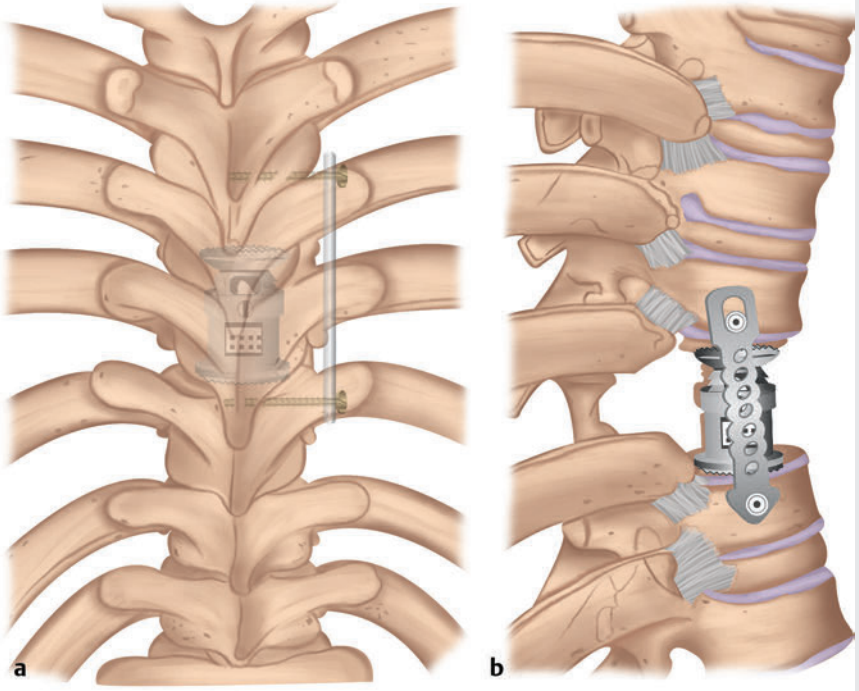

Fig. 33.1 **(a)** Anteroposterior illustration of a thoracic arthrodesis construct using an expandable cage and a posterior instrumentation following corpectomy in a trauma patient. (**b**) Lateral illustration of a thoracic arthrodesis construct using an expandable cage and anterior instrumentation following corpectomy in a trauma patient.

with translation of the spine or rigid spinal deformities. Great care should be taken when anterior column bone quality is poor due to the risk of implant failure or subsidence. Also, many authors recommend avoiding prosthetic spinal implants in the settings of an active pyogenic infection.

33.6 Special Considerations

To promote bone in-growth into and through the cage implant, bone graft or a bone substitute should be used. Depending on the clinical scenario, autogenous bone from the corpectomy site, morselized rib graft, iliac crest graft, allograft bone, ceramic bone substitutes, or even purified bone proteins have been used.

33.7 Special Instructions, Positioning, and Anesthesia

The thoracic and thoracolumbar spine is approached with the patient placed in a lateral decubitus position. The ipsilateral lung may be deflated using double-lumen endotracheal tube ventilation, or ventilation pressures may be decreased allowing visualization of the spine. It is helpful to use neurophysiologic monitoring of the status of the neural elements, depending on the clinical scenario.

33.8 Tips, Pearls, and Lessons Learned

A preoperative identification of the diseased vertebra is crucial prior to surgery. In cases where the vertebral abnormality is not clearly evident on plain films, a sagittal magnetic resonance imaging (MRI) scan that includes the lumbosacral junction and the lesion on the same film is useful, so that the operating surgeon can count the levels up from the sacrum to the lesion using fluoroscopy. A metallic marker placed over the spine may be used to identify the proper location for the skin incision prior to starting. Before starting the corpectomy, the rib heads should be removed to allow identification of the pedicle and posterior corner of the vertebral body. A wide exposure of the involved vertebrae is beneficial to ensure proper alignment of the implant following the corpectomy. Anterior exposure of the vertebra is facilitated by packing small sponges along the anterior aspect of the spine to retract the adjacent blood vessels. Maintenance of the bony endplates of the adjacent vertebrae is important to seat the cage and diminish the odds of subsidence of the cage.

33.9 Difficulties Encountered

Poor localization of the incision or thoracotomy can make proper performance of the corpectomy and alignment of the cage difficult. Bleeding from the corpectomy or epidural vessels should be controlled with hemostatic agents. Ensure proper selection of cage length with the spine in a corrected position by manually applying force to the apex of the kyphotic deformity (push over the spine). This generally reduces the kyphosis at the corpectomy site and prevents undersizing of the cage implant.

33.10 Key Procedural Steps

33.10.1 Approach

A thoracotomy or thoracoabdominal approach is performed in the lateral decubitus position. Segmental vessels are ligated and divided as needed to facilitate the procedure. Three to four centimeters of rib head are removed at the level of the corpectomy to expose the underlying pedicle and posterior region of the vertebral body. The exiting nerve root is protected during the procedure.

33.10.2 Corpectomy

A Kerrison rongeur is first used to remove the pedicle and expose the lateral aspect of the spinal cord. A diskectomy of the adjacent intervertebral disks is then performed. The end plates of the adjacent vertebral bodies are carefully preserved to provide a solid support for the intervertebral cage implant. The anterior portion of the vertebral body is then removed with a rongeur or osteotome. The posterior wall of the vertebral body can be thinned with a high-speed bur and pushed away from the spinal cord with a small angled curette. The posterior longitudinal ligament can be removed to visualize the dura if indicated. In cases without infection or tumor, the bone from the corpectomy site is saved to use as graft to pack in and around the cage implant.

33.10.3 Implant Placement

Any deformity is manually corrected and the defect length is measured. An appropriate cage is selected and packed with bone graft or an appropriate substitute. The corpectomy site is distracted and gentle impaction of the cage is performed. If an expandable cage is chosen, the cage may be introduced into the defect in a collapsed state and lengthened to apply distraction to the spine at the corpectomy site (▶ Fig. 33.1).

33.10.4 Concerns

Ensure that proper placement of the cage is achieved with radiographs or fluoroscopy prior to the completion of the procedure.

33.11 Bailout, Rescue, and Salvage Procedures

If proper cage sizes are not available, use of either allograft bone (e.g., humerus, tibia, femur) or autogenous bone can be considered. If a stable anterior-only construct is not achievable, supplemental posterior instrumentation should be applied.

Pitfalls

- Improper distraction of the spine prior to selection of the cage can lead to residual kyphosis and may predispose to construct failure or back pain.
- Destruction of the bony endplates increases the likelihood of implant subsidence in the postoperative period.
- Malplacement or migration of an unstable cage produces a risk or injury to adjacent vital structures. Additional stabilization with an anterior, posterior, or combined surgical construct should be performed to prevent cage migration, dislodgment, or pseudarthrosis (▶ Fig. 33.1).

34 Anterior Thoracic and Thoracolumbar Plating Techniques

Kelsey Lau, Paul W. Millhouse, Caleb Behrend, and Marcel F. S. Dvorak

34.1 Description

A low-profile anterior/anterolateral plating system can be applied to the thoracic and thoracolumbar spine.

34.2 Key Principles

Anterior thoracic and thoracolumbar plating systems provide additional stability by means of neutralization and load-sharing capacity when combined with reconstruction of the anterior column of the spine.

34.3 Expectations

The primary function of anterior plating is to maintain the alignment of a short segment of the thoracic and thoracolumbar spine following direct anterior decompression of the neural elements. Secondary benefits include the stability provided to anterior interbody grafts, improved rates of surgical arthrodesis, minimizing the number of instrumented motion segments, and the avoidance of the need to augment with posterior instrumentation techniques.

34.4 Indications

The primary indication is thoracic and thoracolumbar segmental instability secondary to anterior spinal column incompetence. This instability is primarily the result of either complete diskectomy or corpectomy for fracture, tumor, infection, degeneration, iatrogenic injury, and failed previous stabilization surgery (either anterior or posterior) resulting in pseudarthrosis.

34.5 Contraindications

The absolute contraindication to anterior plating techniques relates to the inability to obtain secure fixation of the implants in the adjacent vertebral bodies. This may be due to either disease involvement (infection, tumor) of adjacent vertebrae or to severe osteoporosis. Osteoporosis is known to disproportionately affect the cancellous bone of the vertebral bodies, and knowing this, the surgeon is advised to rely more on what cortical bone is preserved. In osteoporosis, posterior hook and wire fixation is preferred, whereas multisegment disease involvement by tumor or infection is optimally stabilized by adding posterior segmental fixation. Anterior plating techniques, functioning primarily as neutralization devices, require an intact posterior tension band (posterior spinal elements) and thus massive disruption of posterior elements by virtue of injury (flexion distraction fractures) or disease (tumor) make this technique less than ideal. The other major limitation of anterior plate fixation is the limited ability to correct deformity through this approach. Translational and rotational deformity cannot be corrected through anterior vertebral body manipulation; thus, these deformities are contraindications to this approach. Newly acquired kyphotic deformities, where there is "plasticity" in the posterior elements can be corrected through an anterior corpectomy, or release followed by the application of pure distraction through the anterior column. Stiff or long-standing kyphotic deformities require combined approaches and are not amenable to anterior plating alone. Relative contraindications include generalized or local osteopenia, pulmonary function prohibiting thoracotomy, and high risk of not being able to be weaned from the ventilator.

34.6 Special Considerations

Detailed preoperative computed tomography (CT) and magnetic resonance imaging (MRI) are required for planning the surgical approach, decompression, reconstruction, and fixation. Pre-emptive estimation of plate size and bicortical screw lengths aids intraoperative decision making. Appreciation of three-dimensional anatomy, particularly of the great vessels, is important. Preoperative angiography may be indicated to identify the artery of Adamkiewicz. Thoracotomy allows access from T3–T11. A right-sided thoracotomy is sometimes recommended due to the position of the aorta on the left and thus avoidance of late vessel erosion. Rib resection should be performed one or two levels above the lesion. An extensile cervicothoracic approach (manubrial resection) may be considered for lesions cephalad to T5 (beware of the thoracic duct on the left side and of the recurrent laryngeal nerve on the right). The 10th rib (Dwyer) thoracoabdominal approach, usually is performed on the left side to avoid the liver, facilitates exposure caudal to T11, and is extensile down to the L5 vertebral body.

34.7 Special Instructions, Positioning, and Anesthesia

Surgery at the incorrect level is a major concern, often underestimated, in all anterior thoracic surgery. Advanced imaging such as CT and MRI often does not aid in the intraoperative determination of the correct level, where poor-quality intraoperative plain films do not facilitate rib visualization or counting up or down the spine. Plain anteroposterior (AP) and lateral scout films on CT or plain radiographs performed preoperatively are mandatory to determine the number of rib-bearing vertebrae, the number of lumbar vertebrae, and the levels of interest. Some techniques that have been used in particularly complex situations (e.g., the obese patient, or obscure anatomy) involve the placement of a needle under the skin, or contrast material in the vertebral body (similar to a vertebroplasty) at the desired operative level in the radiology suite prior to coming to the operating room. Double-lumen endobronchial intubation is required for thoracotomies to allow selective lung deflation. For

thoracoabdominal approaches, the lung can simply be retracted and single lung ventilation is not required. Frequent, intermittent, intraoperative lung expansion reduces postoperative atelectasis. Intercostal nerve blocks may be administered under direct vision prior to any rib resection. Neurophysiologic monitoring is highly recommended for cases in which segmental arteries are to be sacrificed and decompressions performed.

Ensure that the patient is positioned in as true a lateral position as possible, to aid spatial orientation intraoperatively. An axillary roll should be used. The table may be flexed at the required thoracotomy level to aid access. When the patient is positioned, and prior to draping, an AP and cross-table lateral X-ray should be taken to aid in level identification and orientation. At this time, the skin incision level corresponding to the required vertebral level should be clearly marked. These measures will help maintain orientation, optimize screw and plate position, and prevent iatrogenic segmental sagittal and coronal malalignment.

34.8 Tips, Pearls, and Lessons Learned

During the approach, the segmental arteries can be temporarily clamped prior to ligation to determine if there is any alteration in motor evoked potential (MEP) or somatosensory evoked potential (SSEP) signals. The rib head inserts into the superior part of the corresponding vertebra and extends ventrally to obscure a significant portion of the dorsal disk space. The key to an adequate decompression is to resect the rib head, identify the corresponding pedicle and neural foramen, and then proceed with decompression. Furthermore, resection of the rib heads facilitates true lateral positioning of the plate and screws. There is an inherent tendency to drift anteriorly and place the instrumentation in an anterolateral position, where it is more likely to contact the aorta on a left-sided approach. This is particularly risky in the elderly patient with a tortuous aorta, which if it is adjacent to even smooth metal contours, can erode over time as it pulsates against a screw or plate. This has been known to cause fatal exsanguinations to occur in the early and late postoperative time frame. When rod–screw anterior fixation systems are used, great care must be exercised in cutting the rods and positioning them to avoid any sharp burs or edges on the implants that may come in contact with vital intrathoracic structures. Bone graft may be obtained from the resected vertebral body or from the rib resected in the approach. This bone is often placed anteriorly under the anterior longitudinal ligament. In this position, it is visible on follow-up lateral radiographs as it consolidates into a fusion mass. The pleura may then be closed over the bone graft, plates, and screws to prevent intrathoracic migration of bits of bone graft.

34.9 Difficulties Encountered

The most difficult screws to insert are often the screws in the most cephalad vertebra. The orientation of the endplate (following completion of the decompression) guides the screw trajectory and helps determine the screw length. In the presence of tumor, infection, or previous surgery, safe exposure of sufficient vertebral body may be challenging. If amenable, segmental vessels should be tied as well as clipped in case of inadvertent clip loss. During decompression and dissection in the neural foramen, Gelfoam (Pfizer Pharmaceuticals), Avitene (CR Bard), and other hemostatic agents should be available. Plate size constraints cephalad to T3 make an extended anterior cervical approach with sternal split and use of an anterior cervical plate preferable to high thoracotomies.

34.10 Key Procedural Steps

Once exposure, decompression, and anterior spinal column reconstruction are complete, all bony protuberances (endplate osteophytes, rib heads, etc.) should be removed to allow the fixation plate to sit easily on the flat surface of anterolateral vertebral body. Some plate designs, particularly those with "locking screws" do not facilitate lagging of the plate onto the lateral vertebral body cortex and thus positioning the plate along flat lateral cortical surfaces is critical to avoid a proud plate that sits off the bodies (▶ Fig. 34.1). Many of the currently available anterior thoracic plating systems are gently curved to allow the best contour with the required thoracic kyphosis (▶ Fig. 34.2). The holes to be used in the plate should now be identified and fixed with temporary fixation pins or Kirschner wires (K-wires). Intraoperative X-ray or fluoroscopy aids in ensuring optimum trajectory of the screws. Ensure that the screws are parallel to the end plates and angled to avoid inadvertent canal penetration.

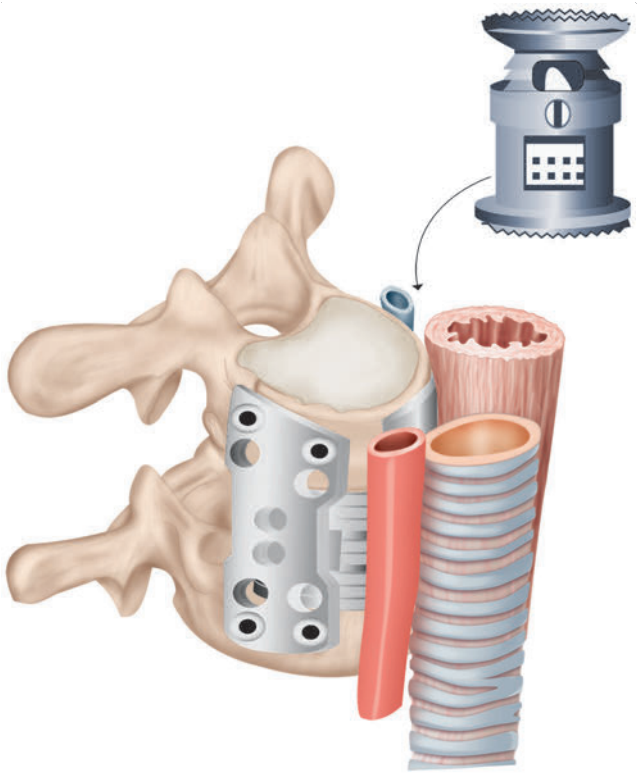

Fig. 34.1 Some plate designs do not facilitate lagging of the plate onto the lateral vertebral body cortex; thus positioning the plate along flat lateral cortical surfaces is critical to avoid a prominent plate that sits off the bodies. Many of the currently available anterior thoracic plating systems are gently curved to allow the best contour with the required thoracic kyphosis.

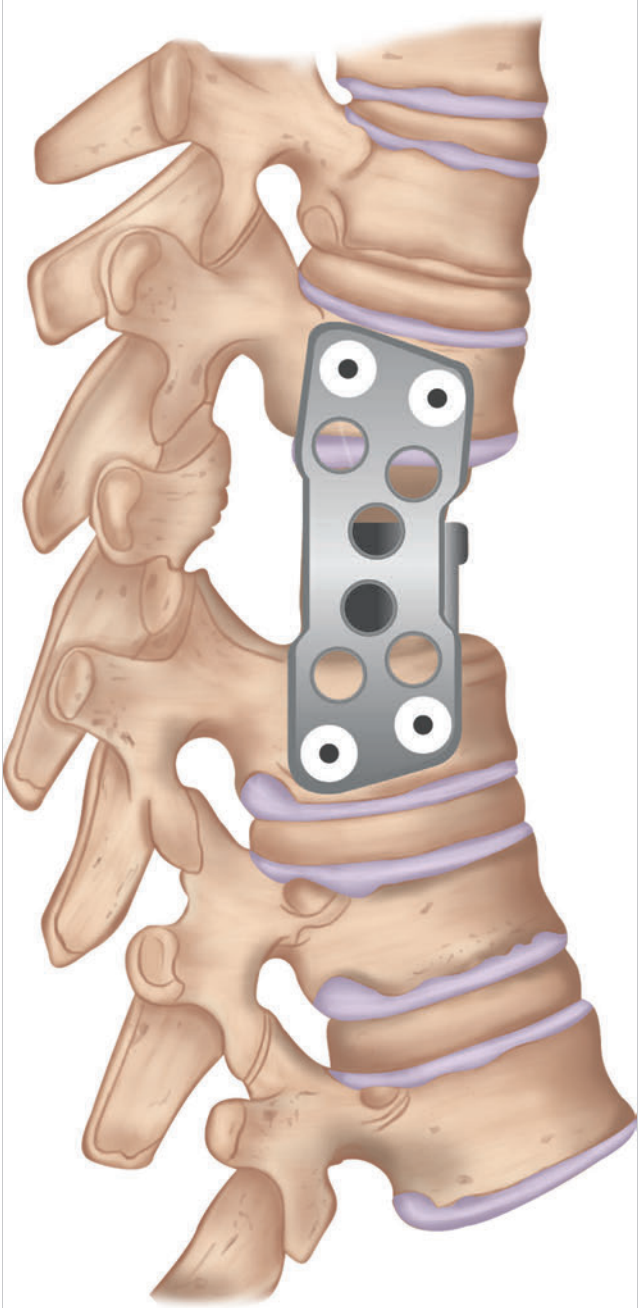

Fig. 34.2 Lateral view illustrating plate in situ. Anterior thoracic or thoracolumbar plates provide neutralization and load-sharing capacity following vertebrectomy when combined with reconstruction of the anterior and middle columns of the spine.

Most systems require the use of bicortical screws, and so care should be taken when passing probes or depth gauges to the far side of the vertebral body. Unicortical locking plate systems allowing ± 5 degrees of screw insertion angulation are also available and are theoretically advantageous in situations of poorer bone quality. Screws should be placed in a convergent manner (anterior screws aimed slightly posterior and posterior screws aimed slightly anterior) to further enhance fixation (▶ Fig. 34.3). As with all bridging plate systems, the plate should be fixed in a compression mode across the interbody reconstruction. Prior to application of the plate, correct alignment must be achieved. Where the table has been aggressively flexed to facilitate exposure, this should be straightened. Furthermore, compression of the graft is often necessary and facilitated by some plate designs.

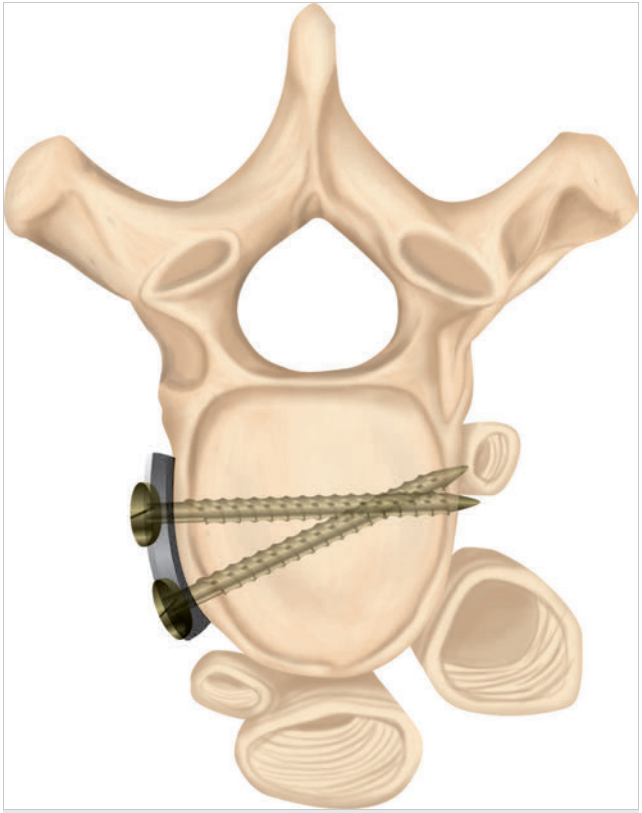

Fig. 34.3 Axial view illustrating how screws should be placed in a convergent manner (anterior screws aimed slightly posterior and posterior screws aimed slightly anterior) to further enhance fixation. Appreciation of three-dimensional anatomy, particularly that of the great vessels, is important.

34.11 Bailout, Rescue, and Salvage Procedures

Remember: You can always abandon anterior fixation and reposition the patient for supplemental posterior fixation. If the deformity cannot be fully corrected from an anterior approach, if the end plates are significantly damaged, or if the biomechanical stability of the anterior construct is suspect, posterior fixation is always an option. By not inserting an anterior plate, further deformity correction can be achieved by means of a posterior osteotomy, but applying an anterior plate in poor alignment makes further posterior deformity correction impossible.

Pitfalls

- Intraoperative spatial orientation may be challenging and suboptimal screw fixation may result.
- Inadvertent fixation in excessive kyphosis must be avoided.
- Bicortical screw placement may result in inadvertent early or late vascular injury.
- Relative osteopenia must be recognized and adequate fixation achieved.
- The requirements to achieve biomechanical stability (adequate anterior spinal column reconstruction combined with adequate plate fixation) must be appreciated.

Section IX

Posterior Lumbar Decompression

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IX

35 Open Lumbar Microscopic Diskectomy

David A. Wong

35.1 Description

Microscopic diskectomy remains the basic "bread and butter" procedure for the spinal microsurgeon. Nevertheless, there are nuances of anatomy, pathology, and surgical technique that can improve outcome and reduce the incidence of complications whether exposure is performed using a tube system or a minimally invasive retractor.

35.2 Key Principles

A firm grasp of the three-dimensional (3D) anatomy of the spinal canal is the prime principle from which an understanding of pathology, surgical planning, and the proper execution of a surgical procedure all flow. A systematic analysis of the anatomy of the spinal canal was outlined in the previous second edition. Ian Macnab's medial to lateral concept (central, lateral recess, foraminal entry/mid/far lateral and pedicular kink) combined with John McCulloch's inferior to superior three-story-house analogy (first story = disk level, second story = lower half of vertebral body with foramen posterior, third story = upper half of the vertebral body with the pedicle posteriorly) gives the surgeon a technique to identify the location and extent of spinal canal pathology (▶ Fig. 35.1). This scheme also allows the surgeon to relate the location of pathology on imaging studies to the intraoperative principal anatomical landmarks (PALS) that will orient the physician once the spinal canal has been entered. Knowing the extent of the pathology and its anatomical relation to the PALS (especially the pedicle), helps the surgeon to determine whether the pathology has been adequately addressed at the time of an operation.

35.3 Expectations

Enhancing the likelihood of a positive treatment outcome for the patient is the fundamental expectation of any surgical intervention. To that end, one must develop the cognitive as well as technical skills to advance good surgical outcomes. As described above, the cognitive expertise for the surgeon to sharpen remains the 3D analysis of anatomy that also allows reliable orientation in the spinal canal at surgery (▶ Fig. 35.1). Advanced technical skills evolve around how the surgeon deals with aspects of the standard anatomy and related pathology.

35.4 Indications

Asymptomatic herniations of the nucleus pulposus (HNP) are common. Some studies have put the rate as high as 20% in the under 60 age group and 36% in individuals older than 60. Thus, the physician must carefully evaluate the patient's history and physical exam and then correlate with imaging studies to determine with a degree of confidence that the herniated disk on imaging is the primary source of symptoms and physical exam findings. Once the diagnosis of a symptomatic herniated nucleus pulposus (HNP) is firm, appropriate nonsurgical care can be implemented. If nonsurgical treatment fails to significantly reduce symptoms and resolve neurologic deficits, then surgical options are indicated. Recognize that early surgical intervention is appropriate in circumstances of cauda equina syndrome, a deteriorating neurologic situation and a debilitating level of pain.

35.5 Contraindications

Other conditions may mimic the symptoms of a herniated disk. If these are determined to be clinically significant, then surgery for a herniated disk may be contraindicated.

Compression of the peroneal nerve at the fibular head is in the differential diagnosis of HNP, particularly when there is a foot drop on physical exam. Look for an associated Tinel's sign at the fibular head.

Irritation of the sciatic nerve by the piriformis muscle in the buttock (piriformis syndrome) may also give rise to radiating lower extremity symptoms.

Other more generalized neurologic conditions also merit consideration in the differential diagnosis of HNP. Neuropathy, most commonly associated with diabetes, but also with vitamin B deficiency, chemotherapy, and other systemic diseases may

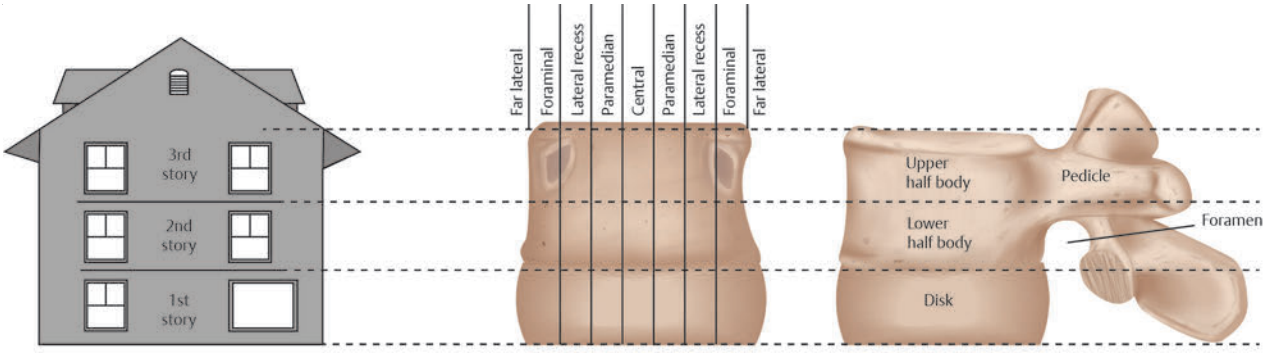

Fig. 35.1 Grid orientation to spine pathology.

give rise to lower extremity numbness and in the later stages, weakness. However, neuropathy most commonly presents with bilateral neurologic complaints and has a patchy, nonradicular distribution of numbness compared to the more typical presentation of a herniated disk most often being unilateral and associated with symptoms and physical findings more specifically in the distribution of the compromised nerve root.

Other less commonly encountered systemic diseases such as multiple sclerosis (MS), Guillain-Barre syndrome, and even West Nile fever have neurologic features and are in the differential diagnosis of lower extremity numbness and weakness.

Vascular claudication rarely occurs in the age group common to HNP.

Any alternate pathology that appears to be a dominant clinical problem must be taken into account in the surgical decision-making process as to whether a surgical diskectomy is indicated or contraindicated.

35.6 Special Considerations

Although HNP may be recognized as the primary diagnosis requiring surgical intervention, other canal pathology may also contribute to neural compromise and clinical symptoms/findings. Facet hypertrophy is the most likely to have a secondary effect contributing to canal and possibly lateral recess and/or foraminal stenosis. Careful analysis of clinical symptoms and findings, correlated to imaging studies is essential to formulating a surgical plan to address all significant pathology. For example, if there is a right-sided herniation at L5–S1, the most likely nerve root to be compromised is the traversing root (S1). However, if the patient also has symptoms and physical exam findings of L5 radiculopathy (numbness of the top of the foot, weak dorsiflexors) the imaging studies should be carefully examined to check for lateral recess/foraminal stenosis from facet hypertrophy that would account for the clinical findings in the L5 (exiting root). If foraminal stenosis is found, then a formal L5–S1 foraminotomy would be included in the surgical plan.

An associated issue is to decide when an adequate decompression has been obtained, particularly if there is a hard component to the disk or a residual protrusion from soft tissue hypertrophy of the anulus and/or posterior longitudinal ligament. Resecting more tissue may lead to additional local scar. We generally pass a nerve probe proximal and distal in the canal, medially and out the exiting root foramen. If the nerve probe passes easily, then we are satisfied that the decompression is adequate.

35.7 Special Instructions, Positioning, and Anesthesia

The Joint Commission (JC) has mandated surgical site marking as part of its effort to reduce wrong-site surgeries (reported under the JC Sentinel Events program). The North American Spine Society (NASS) has its Sign Mark and X-ray (SMaX) initiative to encourage site marking, but also to identify the surgical level in the spine with an intraoperative X-ray. Wrong level is the most common "wrong site" surgery in the spine world. It is our practice for the surgeon to initial the surgical site, but also

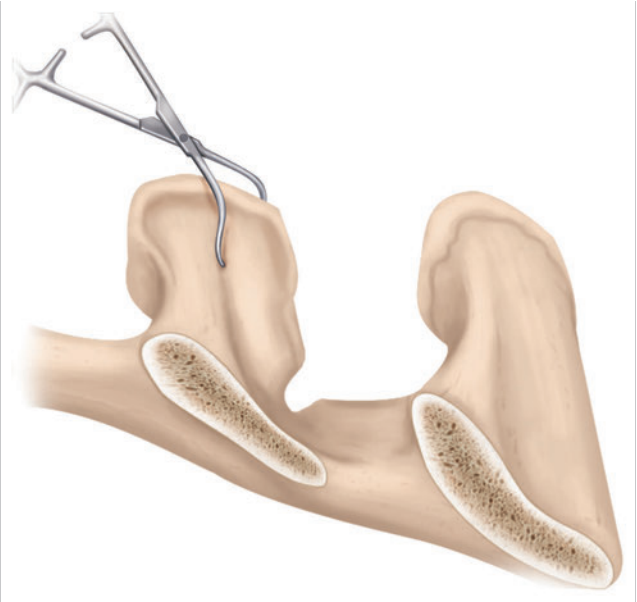

Fig. 35.2 Marker for intraoperative X-ray to confirm surgical level per the North American Spine Society Sign Mark and X-ray program.

to write the surgical level(s) adjacent to the incision location and on the specific side of any planned approach. Beyond the initial skin marking, the NASS SMaX program includes an intraoperative X-ray with a radiopaque marker such as a towel clip or Penfield. This extra step confirms the final identification of surgical level(s) (▶ Fig. 35.2).

Patient positioning is a detail that can enhance outcome. Surgical frames that leave the abdomen free have long been recognized as a method to reduce intraoperative blood loss. Even minor blood loss under the operating microscope can obscure visualization.

Use of an operating frame that positions the patient in a normal lordotic posture is also helpful in determining when an adequate decompression has been performed, particularly with regard to the foramen. Frames adopting a slightly flexed position of the spine open the posterior interlaminar space to facilitate entry into the canal. However, a flexed position also enlarges the foramen in a similar manner to patients in daily life adopting a flexed forward posture to relieve compression of the nerve root in the foramen. Thus, even though a nerve probe may pass out of the foramen in a flexed position, when the patient adopts an upright, lordotic posture, the foramen may be narrower than was apparent at surgery.

Anesthesia also plays a role in minimizing blood loss within the spinal canal. Major hypotensive anesthesia is generally unnecessary for a microsurgical diskectomy. However, medical status allowing, well-controlled blood pressure in the range of 65 mm mean is welcome.

35.8 Tips, Pearls, and Lessons Learned

Another issue in terms of minimizing blood loss is the method by which the ligamentum flavum is removed. Epidural veins

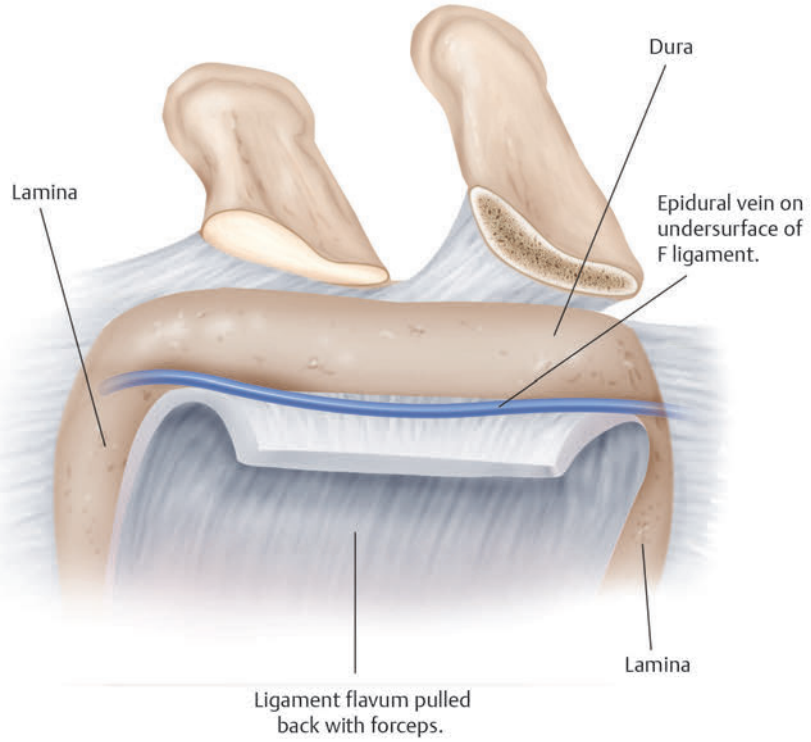

Fig. 35.3 Separation of the ligamentum flavum from the dura.

are often adherent to the undersurface of the ligamentum. If the ligamentum is removed piecemeal with a Kerrison rongeur, these veins are not directly visualized and bleed as they are severed when the ligamentum is excised. A better method is to release the ligamentum proximal and distal from its bony attachments and then enter the canal by incising the ligamentum medially just under the spinous processes. The ligamentum can then be grasped with toothed forceps and retracted slowly laterally. As the undersurface of the ligamentum becomes visible, the adherent epidural veins can be swept off the ligamentum (▶ Fig. 35.3). An instrument with an edge such as a small 2-0 or 3-0 curette works well as the edge of the curette can be used to release any adherent portions of the veins without stretching and tearing the vein.

Vincula are small fibrous adhesions between the dura and ligamentum flavum. In addition to releasing adherent epidural veins, another advantage of the careful separation of the ligamentum from the dura is that vincula can be identified and released as well. If a vinculum is attached to a section of ligamentum being pulled out with a rongeur without separation from its dural attachment then a dural tear can ensue.

35.9 Difficulties Encountered

Thin dura that predisposes to dural tears is always a concern. The dura may be thin in the area of previous epidural steroid injections (ESI). One sometimes encounters plaques of particulate steroid from ESIs on the surface of the dura with thin areas underneath. Take care to carefully separate adhesive areas of the ligamentum from the dura with a small curette to avoid pulling a hole in the dura as the ligamentum is removed.

Thin dura may also be encountered on the undersurface of the superior lamina of a motion segment just above where the ligamentum attaches to the undersurface of the lamina. Above the insertion of the lamina, the dura can become adherent to the bone of the undersurface of the lamina. Care must be taken when releasing the upper insertion of the ligamentum that the dura is not compromised where it may be adherent to bone just above the ligamentum attachment.

35.10 Key Procedural Steps

Studies suggesting that a larger anular defect correlates to a higher rate of recurrent disk herniation have influenced the manner in which the herniated disk is incised at surgery. Our practice has changed from a small "T" incision to a lesser 4-mm horizontal slit incision. This is just large enough to introduce thin pituitary forceps for removal of fragments from the area of a herniation and any loose fragments from the adjacent disk space.

Key to avoiding an inadvertent facet destabilization during the initial exposure/laminotomy is a constant awareness of the location of the lateral border of the pars interarticularis (▶ Fig. 35.4). A medial facetectomy is often performed to expose the lateral border of the dura to address the HNP. With this dissection, our practice is to leave a bridge of bone in the pars area at least 8 to 10 mm wide. A strong pars not only avoids acute facet destabilization, but also reduces the risk of stress fracture in the pars as the patient resumes activities and facet loading. To verify the width of bone, the surgeon must identify the lateral border of the pars. This does not have to be performed by direct visualization. Using an instrument such as a Penfield no. 4 or a small cup curette to feel the lateral border will suffice. Removal of sufficient soft tissue to set eyes directly on the lateral border of the pars often results in an encounter with the neurovascular bundle adjacent to the facet. Cauterizing the

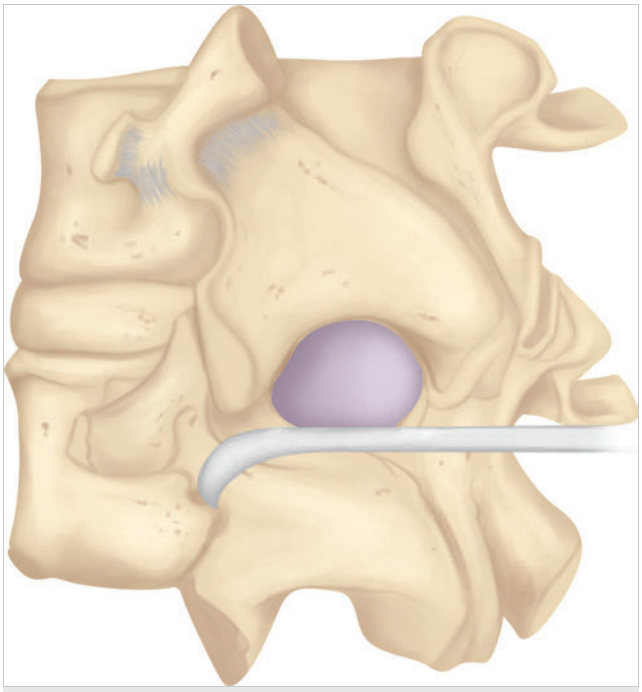

Fig. 35.4 Identification of the lateral border of the pars interarticularis.

resulting bleed also cauterizes the medial branches of the nerves to the paraspinal muscles. This can result in similar paraspinal muscle dysfunction to a facet rhizotomy and is best avoided if possible.

35.11 Bailout, Rescue, and Salvage Procedures

If a durotomy or thin area of dura requires reinforcement/repair, it is helpful to have a "dural repair" tray already assembled. Long Castroviejo needle drivers (▶ Fig. 35.5) are easier to manipulate in a small microsurgical incision or tube. Long, thin bayonet forceps also facilitate the procedure.

A free fragment that has migrated superior or inferior from the level of the disk space may represent a rescue situation. It is sometimes difficult to be sure that the free fragment has been completely removed through a single-level laminotomy. If there is any question of retained disk, the surgeon should have a low trigger for opening the level above or below the segment of primary pathology to ensure that all free fragments have been removed.

Fig. 35.5 Castroviejo needle drivers for dural repair.

Pitfalls

- Tear of the great vessels in the abdomen is the technical issue most likely to lead to a life-threatening situation in lumbar diskectomy surgery. Fortunately, it is a rare complication as complete diskectomy is rarely performed with present surgical philosophy trending towards minimally invasive interventions and avoidance of fusion. Nevertheless, vigilance and an index of suspicion for unexplained hypotension and/or blood in the disk space should be maintained.

36 Open Far Lateral Disk Herniation

Prashanth J. Rao and Ralph J. Mobbs

36.1 Description

This is a technique to access the nerve root and disk pathology lateral to the foramen for removal of a far lateral disk herniation.

36.2 Key Principles

This procedure incorporates a midline or paramedian incision and an approach without entering the spinal canal to maintain the integrity of the facet joint and expose the nerve root (▶ Fig. 36.1, ▶ Fig. 36.2).

36.3 Expectations

A hemilaminectomy and facetectomy may lead to poor long-term results for far lateral disk herniation surgery. Adapting a method to avoid issues of mechanical instability by approaching the impinged nerve root and disk lesion from lateral to the pars/facet joint will improve outcomes.

36.4 Indications

- Single-level radiculopathy secondary to far-lateral disk herniation

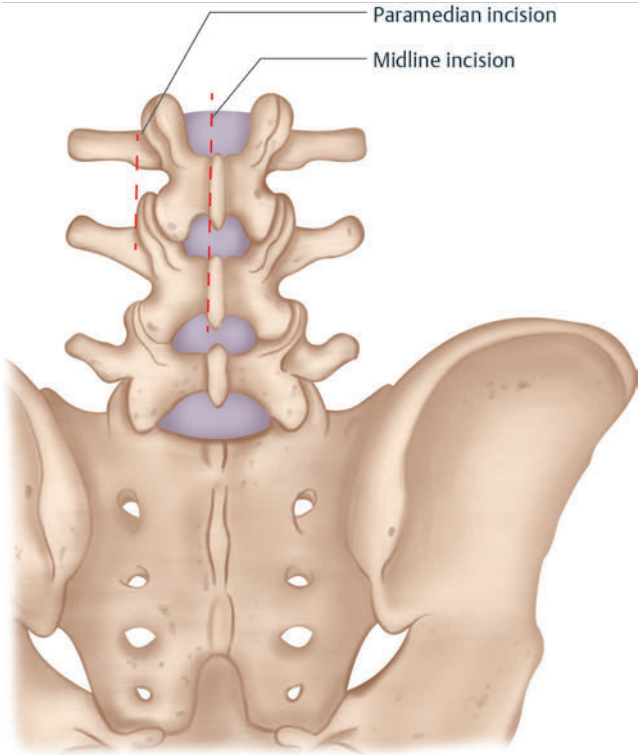

Fig. 36.1 Incision options include midline or paramedian. A midline approach requires a longer incision to expose far lateral to the transverse process and pars; however, it will be more "familiar" anatomy. A paramedian incision will be a shorter, muscle-splitting approach.

- Sensorimotor deficit or radicular pain—failure to improve with conservative care

36.5 Contraindications

- Pathology within the spinal canal
- L5–S1 far lateral disk lesion is difficult to approach from a lateral incision due to the iliac crest; check with preoperative imaging first.
- Spondylolisthesis that requires fusion

36.6 Special Considerations

If a far lateral disk herniation is suspected on computed tomography (CT), it can be confirmed with magnetic resonance imaging (MRI), including parasagittal views.

36.7 Special Instructions, Positioning, and Anesthesia

Position the patient prone on a Wilson frame, Jackson spine table, or a 90/90 Andrews frame. Use X-ray or fluoroscopy to mark out the limits of the exposure prior to skin incision, and then reconfirm when landmarks are exposed. Illumination and magnification are paramount; use either a microscope or loupe/headlight combination. Endoscopy may be an option with tubular retraction devices.

36.8 Tips, Pearls, and Lessons Learned

- The parasagittal T1-weighted MRI reveals the extent of the foraminal pathology.
- If using a paramedian incision, find the plane between the multifidus and longissimus with finger dissection, and palpate the facet joints prior to retractor placement. The distance from the midline can be measured on the preoperative imaging.
- It is easy to "get lost" due to unfamiliarity with this exposure. Define bone landmarks in detail: transverse process, pars, and facet joint.
- Elevate the intertransverse membrane from the inferior edge of the transverse process as it meets with the pars and then mobilize laterally and inferiorly.
- Always have a spine model in the operating room to orient yourself, as the anatomy can become confusing if you rarely perform a lateral exposure.

36.9 Difficulties Encountered

- Bleeding down a deep hole: Maintain strict hemostasis during initial exposure

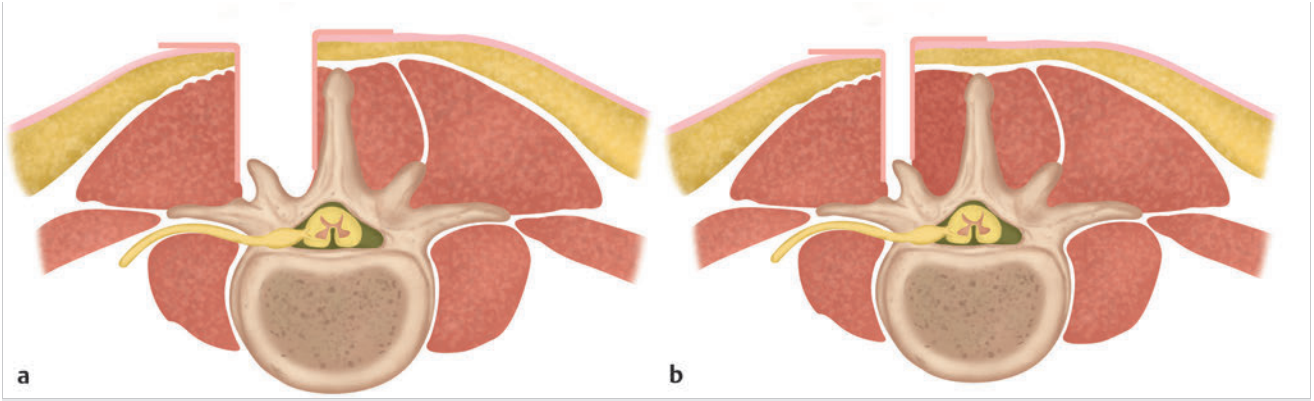

Fig. 36.2 (a, b) A midline incision results in a more painful muscle dissection and retraction combination. The paramedian incision is a more direct route to the pathology; however, it is an unfamiliar approach.

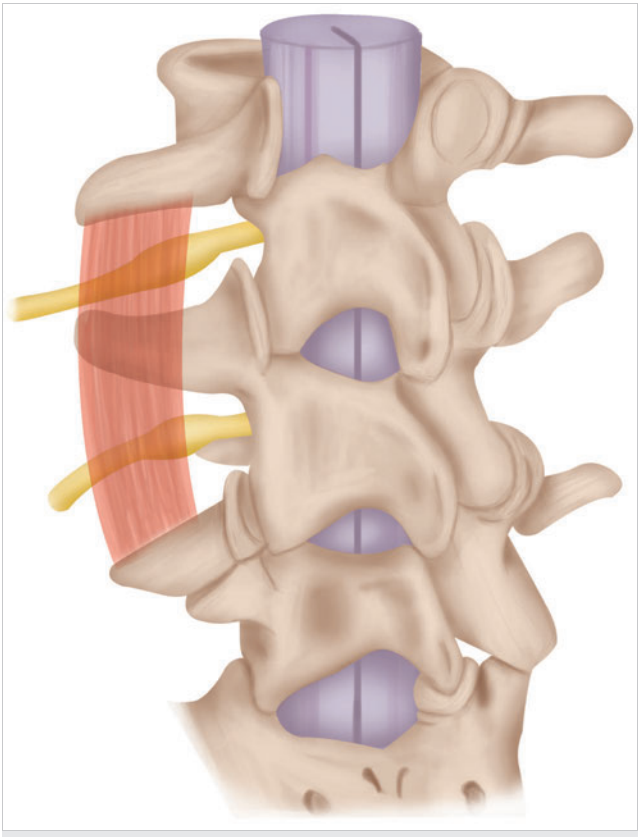

Fig. 36.3 After the initial exposure, the following landmarks must be seen before proceeding with nerve exploration. In this case, for a L3–L4 far lateral disk resulting in L3 nerve root impingement, the transverse process and pars of L3 must be clearly visualized. In addition, the L3–L4 facet joint and L4 transverse process should be seen to delineate the intertransverse membrane prior to incising this structure.

- A consistent radicular vessel will be found lateral to the facet joint/pars: Use bipolar cautery.
- The impinged nerve root may be effaced against the intertransverse membrane: Care should be taken when elevating.
- If a large hypertrophied facet joint is overlying the nerve, be prepared to remove some lateral and superior joint for exposure.

36.10 Key Procedural Steps

- Obtain X-ray *prior* to skin incision to define level.
- During muscle and bone dissection, preserve the facet capsule.
- Key bone landmarks must be seen (▶ Fig. 36.3, ▶ Fig. 36.4, **Video 36.1**): Transverse process, pars interarticularis (pars), and facet joint. Reconfirm levels with X-ray when anatomical landmarks are exposed.

36.11 Bailout, Rescue, and Salvage Procedures

If the anatomy is confusing, extend the incision to identify more normal anatomy especially medially, where you can work on either side of the pars and identify the root in a more familiar setting.

Pitfalls

- Bleeding that is difficult to control: Pressure, FloSeal (Baxter Healthcare), Gelfoam (Pfizer Pharmaceuticals), and bipolar cautery
- Difficultly finding the nerve root: Refer to T1-weighted MRI and recheck level with fluoroscopy
- Elevate the intertransverse membrane from the inferior aspect of the superior transverse process.
- Disk location instead of being inferior to the nerve root could present itself anterior to the nerve root or superior to nerve root and between the nerve root and the pedicle (▶ Fig. 36.5).
- Mobilize nerve superiorly to access disk herniation.

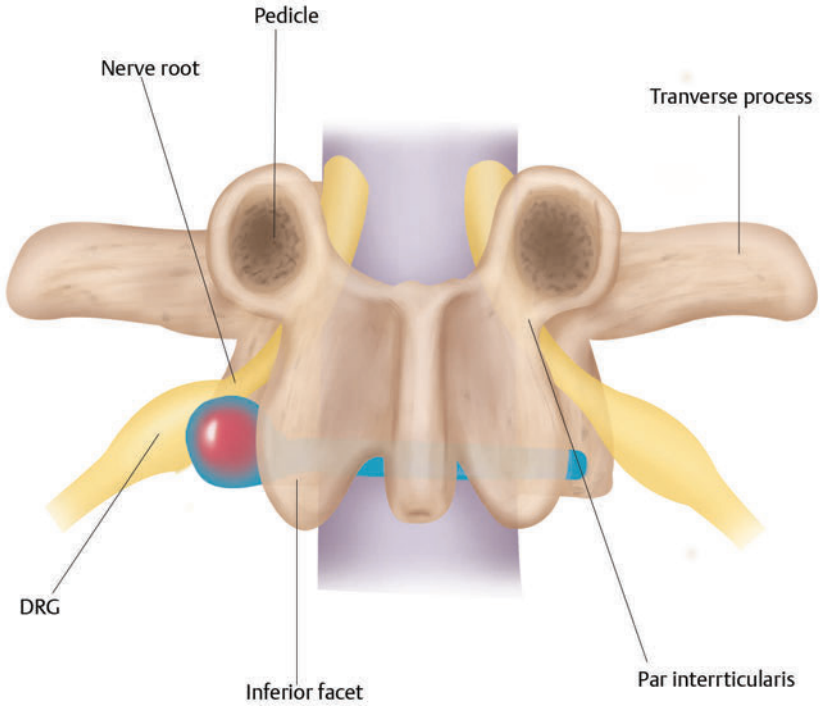

Fig. 36.4 Note the course of the L3 nerve root. Most far lateral disk herniations will push the nerve root superiorly against the L3 pedicle. Depending on the patient's individual anatomy, some bone from the pars and facet joint may require removal to clearly visualize the course of the L3 nerve root prior to disk removal. DRG, Dorsal root ganglion.

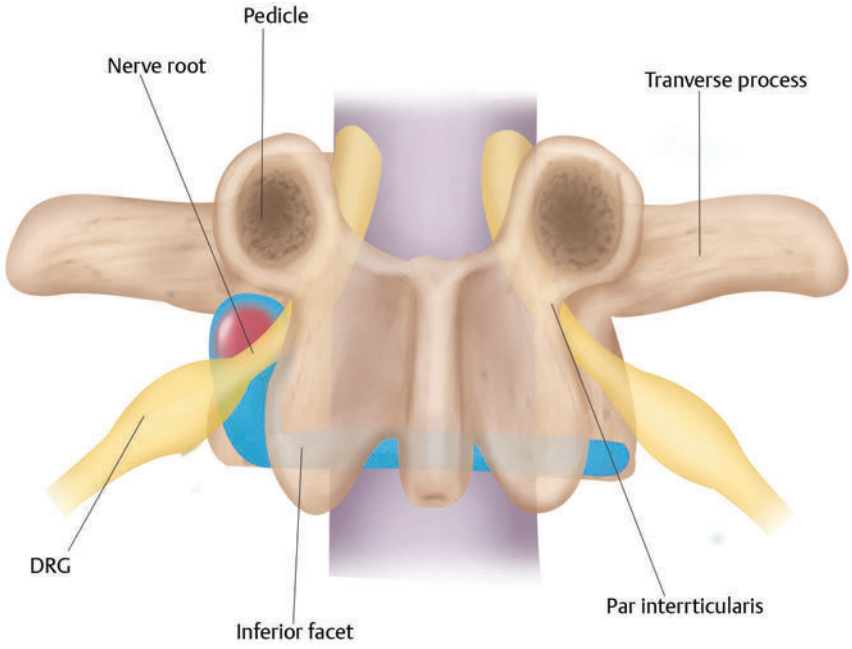

Fig. 36.5 Rarely, the disk herniation can be anterior to the nerve root or superior to the nerve root and between the nerve root and the pedicle. Hence, it is advised to check above and in front of the nerve root to check for any fragments. DRG, Dorsal root ganglion

37 Open Laminectomy, Medial Facetectomy, and Foraminotomy

William Neway, Stephen Pehler, and Peter G. Whang

37.1 Description

These techniques adequately and safely achieve neural decompression in the lumbar spine below the level of the conus while protecting the neurologic structures.

37.2 Key Principles

While maintaining lumbar motion segment stability, adequate neurologic decompression of the spinal canal and nerve roots via laminectomy, partial facetectomy, and foraminotomy is safely achievable without injury to the neurologic structures or dura.

37.3 Expectations

The relief of neurogenic claudication and/or radiculopathy is an achievable goal via the combination of laminectomy, facetectomy, or foraminotomy. A meticulous and adequate decompression leads to few complications and rapid relief of symptoms in the majority of patients. With relatively minimal rehabilitation and hospital stay, patients can expect to return to their activities of daily living within a brief period.

37.4 Indications

Clinical symptoms of neurogenic claudication or radiculopathy and radiographic confirmation of stenosis or nerve root compression.

37.5 Contraindications

- Lack of correlation between radiographic and clinical findings
- Evidence of instability and/or deformity on imaging studies
- Medical comorbidities that prohibit reasonable surgical risk
- Local skin conditions increasing risk of postoperative wound complications: Eczema, psoriasis, decubiti, and other assorted superficial infections

37.6 Special Considerations

A thorough comprehension of the local spinal anatomy contributing to the patient's stenosis is needed to completely decompress the neural elements. Preoperative correlation between physical exam, symptoms, and radiographic findings must be in harmony to optimize postsurgical outcomes. The elderly and patients with multiple medical comorbidities should have preoperative risk stratification and optimization to lessen the likelihood of perioperative complications.

37.7 Special Instructions, Positioning, and Anesthesia

General anesthesia is most commonly utilized for surgical decompression. However, regional anesthesia may be employed if specific indications warrant. In either option, the patient is placed in the prone position with the hips and knees flexed. Depending on surgeon preference or patient limitations, the kneeling position may also be used. In the flexed position, lumbar lordosis is decreased with the interlaminar space increased. Whichever position is chosen, the abdomen must hang free to decrease intra-abdominal pressures, therefore decreasing epidural venous plexus pressures, ultimately decreasing intraoperative blood loss. Special attention should be given to the head, orbit, and extremities, with bony prominences appropriately padded to avoid iatrogenic neurologic and pressure injuries.

If spinal anesthesia is employed, the puncture site must be cephalad to the planned laminectomy site to prevent cerebrospinal fluid leak postoperatively.

37.8 Tips, Pearls, and Lessons Learned

Confirmation using intraoperative imaging is mandatory to identify the correct planned level of decompression. Anatomical landmarks are beneficial, but preoperative notation should be made of common variants. These include sacralization or lumbarization of the lowest lumbar segment or first sacral segment, respectively. These variations are relatively common and can lead to intraoperative confusion, and ultimately wrong-level surgery. Additional adjuncts to visualization can be used including a microscope or loupes with a fiberoptic headlight.

Careful preoperative imaging studies can assist in avoiding an inadequate decompression. For instance, full computed tomography (CT) visualization of the entire lumbar spine from L1–S1 is needed to ensure that cephalad segments are not included in the pathology.

37.9 Difficulties Encountered

Adhesions between the ligamentum flavum and the dural sac are often encountered in patients with severe stenosis or in the presence of synovial cysts. Meticulous surgical technique is critical in avoiding inadvertent dural tears during decompression. Also, elderly patients tend to have a more fragile dural sac, increasing the risk of iatrogenic durotomies.

37.10 Key Procedural Steps

After confirmation of the indicated levels for decompression, the interspinous ligament and the spinous process of the

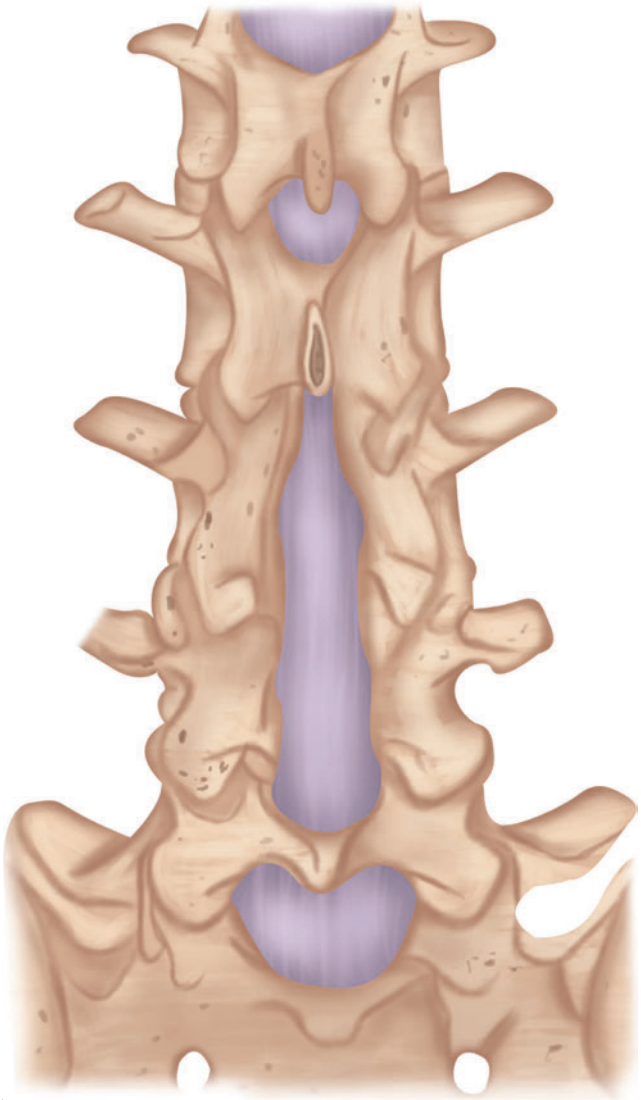

Fig. 37.1 A central laminectomy has been performed by removing the spinous process, central lamina, and the ligamentum flavum.

involved segment are removed using a Leksell rongeur. An option to remove half of the superior spinous process or half of the inferior spinous process can be used. To proceed with decompression of the central portion of the spinal canal, use of a rongeur or high-speed bur can utilized to thin the lamina. Next, using a Kerrison rongeur moving from a caudal to cephalad direction, complete decompression of the lamina can be completed (▶ Fig. 37.1). To assist in protecting the underlying dura, an option to leave the ligamentum flavum in place can be considered. There must be careful identification of the pars interarticularis, specifically the lateral border, to prevent iatrogenic removal or thinning, which would ultimately lead to fracture and/or instability.

Partial removal of the medial facet using a Kerrison rongeur allows for lateral recess decompression. As an alternative, the medial aspect of the inferior articular facet may be removed using an osteotome or a high-speed bur, after which a portion of the underlying superior articular facet is then excised. To

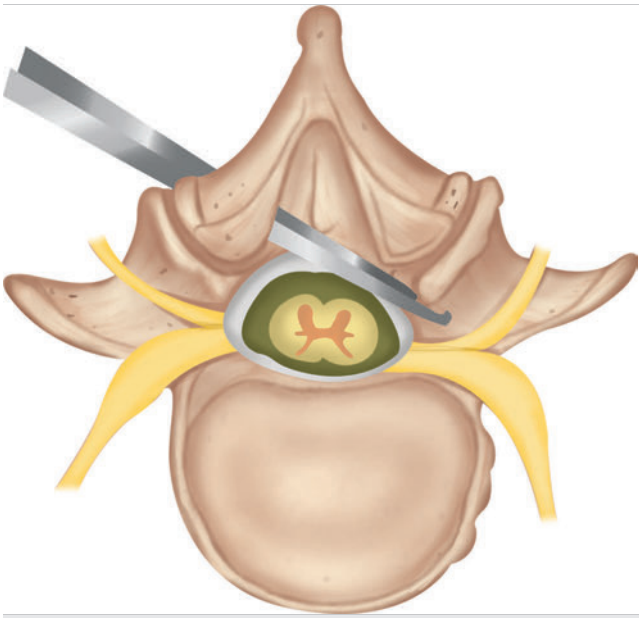

Fig. 37.2 Axial view of lateral recess decompression.

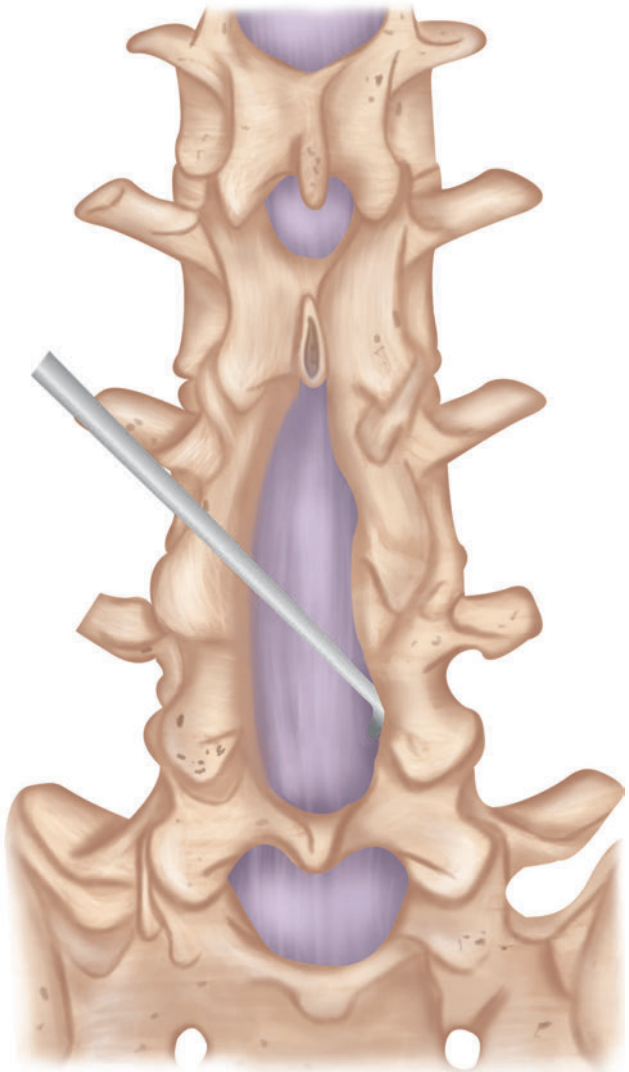

Fig. 37.3 Foraminal decompression is assessed by placing a blunt dissector into the neural foramen.

complete the lateral recess decompression, removal of the ligamentum and osteophytes out to the medial wall of the pedicle is completed. From a technical standpoint, lateral recess decompression is best achieved by the surgeon on the opposite side of the table (▶ Fig. 37.2). Again, during the decompression, care must be taken to not violate the pars interarticularis.

As with lateral recess decompression, foraminotomies are also best technically performed from the opposite side of the table. Intraoperative identification of the adjacent pedicle will allow for anatomical visualization of nerve root take-off from the dural sac. Tracing this take-off to the foramen, allows for adequate decompression in route. A curette or Kerrison rongeur can be used to remove dorsal pathology from the foramen. Palpation using a blunt dissector (often a Woodson elevator) can be placed into the foramen to confirm a complete decompression (▶ Fig. 37.3).

Hemostasis of the epidural venous plexus is a critical portion of the procedure. This can be achieved using bipolar electrocautery, or any numerous forms of collagen sponges or commercially available thrombin. However, it is important to remove any potential space-occupying hemostasis adjuncts to prevent neurogenic compression. If excellent hemostasis is obtained, the use of subfascial drains is not indicated. In the setting of larger or multilevel decompressions, or patients with coagulopathy, drains may be used at the surgeon's discretion.

37.11 Bailout, Rescue, and Salvage Procedures

In the event a dural tear is encountered, watertight closure is imperative. If possible, primary closure of the defect with suture, such as 4–0 NUROLON (Ethicon), is preferred. However, this is not always obtainable. Alternative techniques including synthetic matrices or fibrin glue can be employed.

Pitfalls

- To avoid iatrogenic neurapraxic injury, careful attention must be paid to excessive retraction or compression of the neural elements.
- Inadequate decompression may cause persistent symptoms postoperatively.

38 Safe Exposures in Revision Surgery

Rajiv Taliwal

38.1 Description

With the increase in the total number of spine procedures performed, there is a higher likelihood of encountering a patient with surgical indications who has already had a previous operation. While the basic principles of surgical decompression apply, special considerations need to be addressed to ensure a safe and effective outcome.

38.2 Key Principles

The key to surgery is safe dissection and exposure. Regardless of the size of the incision or the extent of the operation, proper visualization is important. In a revision setting, many traditional landmarks are gone or altered. Nonvisual cues such as palpation can be misleading. The remaining tissues behave differently. Scar tissue can have a different tactile feel and be more adherent. This can blur tissue planes, especially between the dura mater and surrounding bone or soft tissue.

38.3 Expectations

Despite previous surgery, the spinal canal should be adequately decompressed and nerve roots mobilized and free to glide. This should be done with minimal disruption to surrounding soft tissues and bony structures that maintain alignment and stability. The facets and pars should be preserved to avoid iatrogenic instability. Preoperative discussion should focus on appropriate indications and levels to address. Operative time, blood loss, postoperative recovery, and long-term outcomes are less predictable on a revision procedure.

38.4 Indications

Recurrent neural compression can occur after previous attempts at decompressive surgery. Malalignment or instability caused by trauma, degeneration, tumor, infection, or iatrogenic reasons after a previous procedure can result in the need for repeat surgery. Often, junctional degeneration above or below previous surgical levels may require working through altered tissue planes and extending the previous decompression.

38.5 Contraindications

If an alternative approach is viable, one should avoid operating through previous scar tissue. History of previous dural injury should be considered, at least in terms of being prepared for recurrent dural defects. Chronic nerve injury refractory to surgical treatment may not be worth the risk of revision surgery.

38.6 Special Considerations

Obtaining records of previous surgery can be helpful, especially if any untoward issues were encountered such as dural defects, conjoined nerve roots, or other anatomical anomalies. Appropriate preoperative imaging should include radiographs with dynamic flexion and extension images to ensure spinal stability. Magnetic resonance imaging (MRI) with contrast can help distinguish epidural scar tissue from bony or disk-related nerve root compression. If previous hardware obscures MRI, computed tomography (CT) myelography can be helpful, especially to visualize hardware placement and bony fusion or pseudarthrosis.

A radiolucent table such as a Jackson frame is used if possible to assist spinal imaging to confirm levels as well as identify spinal landmarks in both the anteroposterior and lateral plane. Good lighting and loupe or microscopic visualization enhance surgical accuracy and can limit inadvertent complications. Good retractors are helpful, especially in the obese patient. Appropriate long instruments can give the surgeon better access to deep tissues. Hemostatic agents should be available in case of unexpected bleeding. Dural repair or patch materials should be readily available, and the patient should be counseled about the increased risk of dural injury and the possibility of bedrest postoperatively.

38.7 Special Instructions, Positioning, and Anesthesia

Prep widely to allow for extensile exposure. Go from known to unknown anatomy. You may need to work “around” scar tissue rather than go through it. Anesthesia should have good intravenous access in case of excessive blood loss. Consider Foley catheter in case of dural defect requiring postoperative immobilization and flat bedrest.

38.8 Tips, Pearls, and Lessons Learned

Take advantage of natural tissue planes to minimize blood loss and “getting lost.” Splitting muscle fibers is preferred to get to bone and stay on it. Expose normal tissues around the scar and work from known to unknown anatomy. Blunt dissection with a Cobb elevator wrapped in a sponge can help peel away scar tissue. Once the medial border of the remaining facet joint is identified, an angled curette can be used to lightly peel away scarred dura from bone. With the round edge toward the canal, the sharp edge of the curette is gently guided down the medial border of the facet joint. Once the plane is identified, it is easier to continue neural dissection from inside the canal.

It is safer to work around adherent tissue rather than force through it and risk a dural tear. Removing bone and ligament is just as important as mobilizing scarred-in nerve roots that no longer glide in the foramen. An angled osteotome can be used to make a defined cut in the facet joint. We will sometimes leave the scar attached to the dura and mobilize the bone around it to remove bony pressure effectively and mobilize the neural elements. Wider facet resection is sometimes necessary.

It can be difficult to know when to keep pushing forward and when to accept that scar is too tough to negotiate without dural injury.

38.9 Difficulties Encountered

One can easily lose track of depth and position and inadvertently apply Bovie cautery too deep in the initial approach. It is better to start in the middle and get to the sides quickly. When in doubt, have a low threshold to check radiographs to confirm position. Previous hardware can provide landmarks, but may cause dural injury if contacted with electrocautery.

38.10 Key Procedural Steps

Once adequate imaging and positioning is confirmed, we prefer to use a radiolucent table in case intraoperative fluoro imaging is needed. Mark levels with an 18-gauge needle and obtain preoperative imaging. The previous incision should be used, but may need to be extended above or below. Try to avoid skin bridges with paraspinal incisions too close to the original scar. Superficial tissue can be edematous, rubbery, hyper- or hypovascular. Try to find and isolate the dorsal fascia first before incising it. Better exposure will ensure a better closure, and this layer is important if a dural defect is encountered.

Midline bony structures should be identified on preoperative films. If not present, identify the last remaining levels above and/or below scar level. Once the midline is established, one can then work around to the level of the facet joints on either or both sides. In general, we prefer to avoid diving directly down the middle unless known laminar structures are present. Dural depth can be deceiving and easily breached accidentally. Furthermore, there is little value to decompressing scar in the middle of a laminectomy site because most of the symptomatic stenosis is subarticular or foraminal.

Once the facets and pars interarticularis are identified, it is best to work from known lateral to medial anatomy. Excessive electrocautery can disrupt the facet capsule and result in iatrogenic instability in an already decompressed segment. Also, arcing current can disrupt the fragile dura. Care should be taken dissecting around previous instrumentation, as crosslinks and rod constructs can sometimes be close enough to dura to conduct electric charge and cause a thermal dural defect.

38.11 Bailout, Rescue, and Salvage Procedures

Consider achieving surgical objectives via a different approach to avoid scar tissue. Foraminal stenosis can be approached from a far lateral decompression working medially toward the scar. Anterior interbody fusion can provide indirect decompression by foraminal height restoration. During a standard decompression, one may need to perform more aggressive bony resection of the facets or pedicles, which may require fusion to stabilize the segment. Be prepared to fuse in advance and discuss the possibility preoperatively.

Pitfalls

- Dural defects often require complex repairs, as tissues are more adherent and may require a patch for repair.
- Nerve stretch may result in neurapraxia, with postoperative foot drop or other motor loss.
- Blood loss from muscle bleeding or unexpected neovascularization can be more than usual.
- Excessive decompression can lead to iatrogenic instability.
- Chronic nerve irritation can result in poor clinical outcomes despite best efforts and good clinical techniques.

Section X

Posterior Lumbar Arthrodesis and Instrumentation

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39 Lumbar Pedicle Screw Placement

Abhijeet Kadam, Paul W. Millhouse, Alexander R. Vaccaro, and Robert W. Molinari

39.1 Description

Pedicle screws are safely and accurately placed in the lumbar spine with particular emphasis on avoidance of intraoperative and postoperative complications.

39.2 Key Principles

Pedicles are short conical pillars with an oval-shaped cross section, which allow for placement of screws traversing the anterior and posterior vertebral columns during posterior instrumentation. This permits the application of compression, distraction, rotation, and translation forces selectively at individual spinal segments. Another distinct advantage is their ability to be applied for fixation regardless of the status and integrity of the posterior osseoligamentous vertebral structures. Thus, pedicle screw systems can be reliably used even in cases of previous wide laminectomies or posttraumatic disruptions of the laminae, spinous processes, and/or facets. To maximize hardware purchase within the lumbar pedicles, the screws should be directed through the center of the pedicles into the vertebral body. They should converge toward the midline to ensure avoidance of the lateral vertebral body and penetration of the pedicle wall.

39.3 Expectations

The goals of lumbosacral segmental instrumentation are to provide intersegmental stability and reduce deformity (such as that seen in scoliosis, spondylolisthesis, kyphosis, and trauma). Screws placed into the pedicles may be used as reliable points of anchorage, enhancing construct rigidity, and improving the likelihood of successful fusion and maintenance of spinal alignment.

39.4 Indications

- Reduction and fusion of isthmic and degenerative lumbar spondylolisthesis
- Reduction and stabilization of lumbar burst and compression fractures
- Instability arising from primary or secondary neoplastic lumbar lesions
- Stabilization following wide lumbar decompression for spinal stenosis
- Revision surgery for symptomatic lumbar pseudarthrosis
- Stabilization after lumbar vertebral osteotomies
- Augmentation of anterior lumbar interbody fusion
- Scoliosis correction and stabilization

39.5 Contraindications

- Severe osteopenia and osteoporosis
- Inadequate pedicle size or morphology
- Fractured or diseased pedicles
- Presence of active infection such as vertebral osteomyelitis

39.6 Special Considerations

Patients with severe osteoporosis may not be suitable for lumbar pedicle screw fixation. Bone density less than 0.45 g/cm^2 has been associated with pedicle screw loosening and pullout. A subjective estimate of the screw's degree of purchase in the bone can be made from the insertional torque required to place it in the pedicle. Modifications to the insertion technique such as undertapping, no tapping, and the use of conical screws have been shown to improve screw pullout strength. Approximately 75% of screw purchase is obtained in the pedicle; for additional purchase in the vertebral body, the screws should cross the midportion of the vertebra in the axial plane. Typically, 6-mm-diameter and 40- to 45-mm-length screws are required in the lumbar spine. Although penetration of the anterior lumbar body cortex enhances screw pullout strength by 20 to 25%, doing so increases the likelihood of vascular injury and is therefore not recommended. As a rule of thumb, the depth of insertion of the pedicle screw should be between 50 and 80% of the width of the anteroposterior diameter of the vertebral body on a lateral fluoroscopic view. This provides a safe zone for the screw to avoid penetrating the anterior vertebral body wall.

39.7 Special Instructions, Positioning, and Anesthesia

A radiolucent table is imperative for proper anteroposterior (AP) and lateral intraoperative imaging during screw placement if fluoroscopy is used. Positioning the hips in extension improves lumbar lordosis. Fusing multiple segments of the lumbar spine with the hips positioned in flexion may cause iatrogenic flatback deformity. General anesthesia is used in patients undergoing lumbar pedicle screw instrumentation.

39.8 Tips, Pearls, and Lessons Learned

Appropriate positioning of transpedicular screws in the lumbar spine is dependent on proper visualization of the posterior anatomical landmarks for insertion. Knowledge of the anatomy of the pedicle in relation to the neural structures is crucial. The nerve root is situated just medial and inferior to the pedicle as it exits into the intervertebral foramen. Violation of the inferior pedicle cortex in this area may cause injury to the exiting nerve root.

The amount of medial angulation of the pedicle varies depending on the level and on the location of the surgeon's entry point. Lateral entry points on the transverse process require greater medial angulation. The screws should be angled approximately 5 degrees medially at L1, 10 degrees at L2, and progressively increasingly angulated to 15 degrees at L5 (▶ Fig. 39.1). The sagittal plane angulation must also be accounted for in achieving the optimal trajectories of screw placement. In a properly positioned patient, with the hips

extended to maintain lumbar lordosis, the sagittal pedicle angle at the L4 lumbar level is usually zero degrees. The lordotic curve of the lumbar spine necessitates increasingly rostral angulation for the upper lumbar levels, whereas for the L5 pedicle, the optimal sagittal angle is 5 to 10 degrees caudal. Preoperative imaging studies should be used to determine the exact angulation, depth, and size of the pedicles. Intraoperative AP fluoroscopy will reliably identify the starting point in relation to the pedicle walls.

Continuous intraoperative fluoroscopy in the plane of the pedicle, while simultaneously moving the ball-tip feeler probe through the pedicle tract, is a helpful technique to assess the screw trajectory. Stimulus evoked or triggered electromyogram monitoring is also invaluable in determining screw accuracy and detecting medial and inferior pedicle wall breaches.

39.9 Difficulties Encountered

Distortion of the posterior anatomy by the presence of a fusion mass, pseudarthrosis, or scar tissue may preclude precise identification of normal anatomical landmarks for screw insertion. Intraoperative fluoroscopy or a three-dimensional navigation imaging device may be helpful in these cases. Performing a laminotomy and palpating the medial, superior, and inferior borders of the pedicle is a technique that may enable accurate placement of pedicle screws in cases where satisfactory imaging proves unobtainable.

39.10 Key Procedural Steps

The ideal entry point for the pedicle is at the intersection of a vertical line tangential to the lateral border of the superior articular process and a horizontal line passing through the middle of the insertion of the transverse process, or 1 mm below the joint line (▶ Fig. 39.2). AP imaging can be used to determine the location of the pedicle and its relation to the chosen starting point. The cortical bone overlying the entry point is removed with a bur, rongeur, or awl to expose the underlying cancellous bone, after which the pedicle is palpated with a probe (▶ Fig. 39.3). A lateral entry usually requires more medial angulation, and a medial starting point may not require any angulation of the pedicle probe. The typical lumbar pedicle is elliptical in cross section, with the larger diameter oriented vertically. This shape facilitates variable angular positioning of the probe in the sagittal plane (▶ Fig. 39.4). A swirling or wiggling motion is used to advance the pedicle probe gently through the cancellous center of the pedicle and into the vertebral body. Sudden loss of resistance during insertion almost certainly indicates that the probe has violated the pedicle wall. The instrument should be removed and the entry hole and tract felt with a semiflexible ball-tip feeler probe to determine whether penetration has been medial, lateral, superior, or inferior. After this has been ascertained, the pedicle probe can be properly redirected into the pedicle isthmus. Probing the four walls and the floor of the pedicle tract with the ball tip is a good way to determine the accuracy of the screw tract within the pedicle. Placing a marker in the pedicle and obtaining AP and lateral radiographs also helps to determine tract position (▶ Fig. 39.5). The optimal length of the screw can be determined by measuring the length of an inserted Steinmann pin, Kirschner wire, or pedicle probe from the pedicle entry site to a depth of 50 to 80% of the anteroposterior vertebral body width. If tapping the screw tract, the isthmus of the hole should be tapped with a tap of slightly smaller diameter than the screw, to optimize screw purchase.

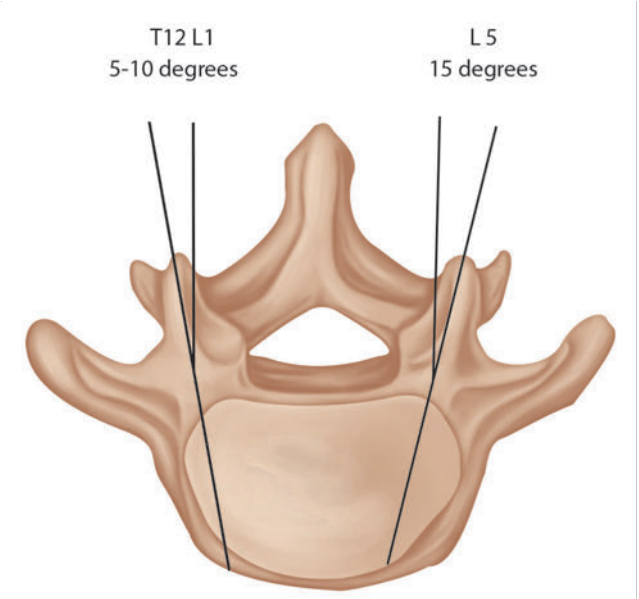

Fig. 39.1 Various entry points and inclinations have been described. A lateral converging approach spares the facets of the unfused levels.

39.11 Bailout, Rescue, and Salvage Procedures

When screw purchase is compromised, placement of a larger-diameter screw can often serve as an appropriate rescue technique. If a cortical breech has not occurred, a small amount of polymethylmethacrylate or fine corticocancellous bone chips can be inserted into the screw tract to improve purchase. If the posterior elements are intact, a laminar hook or sublaminar wires

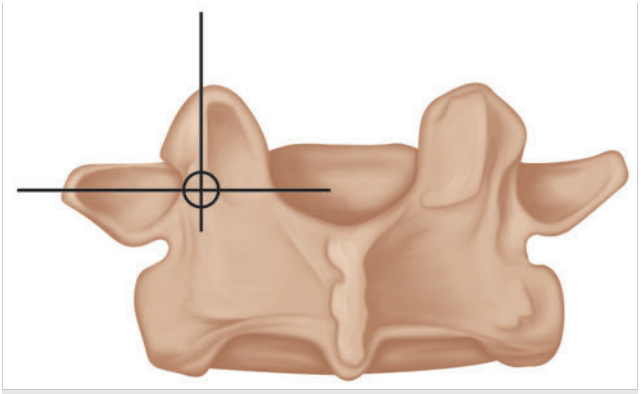

Fig. 39.2 The entry point for the pedicle is at the intersection of a vertical line tangential to the facets and a horizontal line bisecting the transverse process. Screw convergence increases as one moves caudally.

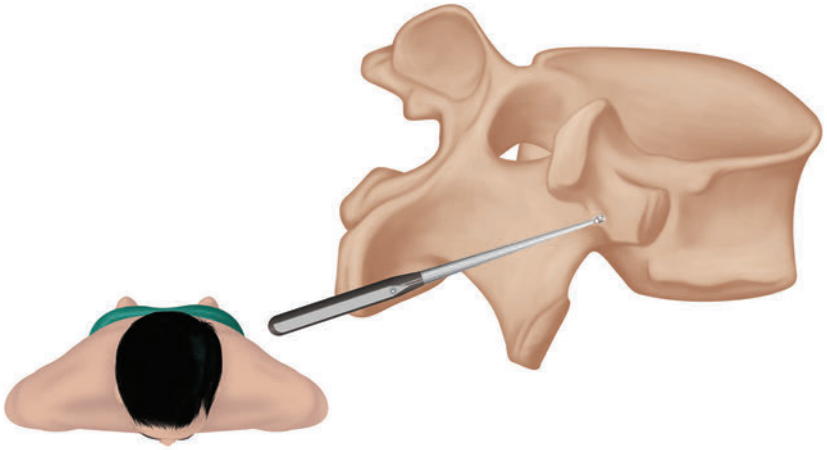

Fig. 39.3 After a blunt pedicle probe or curette is used to initiate the screw tract, the tract is tapped.

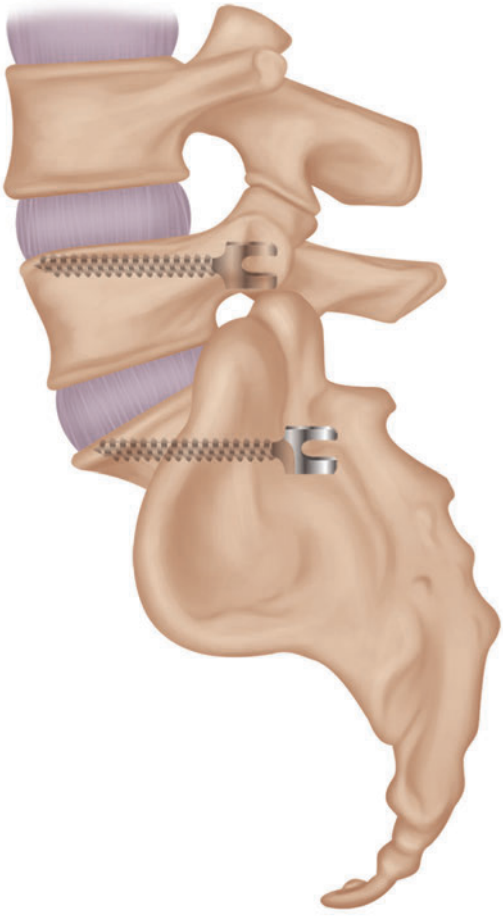

Fig. 39.4 Lateral view demonstrating proper placement of pedicle screws. Screws should parallel the end plate or angle slightly upward.

may be used in place of a pedicle screw. Other options include adding another level of fixation above or below, or avoiding additional instrumentation and relying on the contralateral construct only. Lastly, removal of instrumentation and performing an uninstrumented fusion may be necessary as the final bailout procedure in some cases.

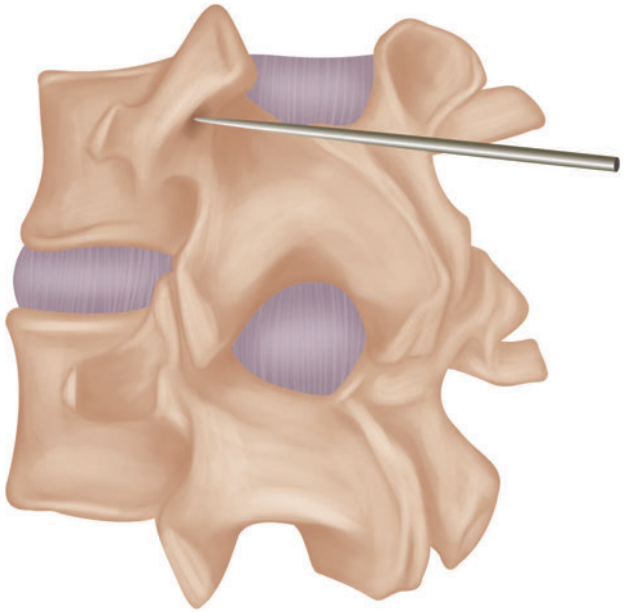

Fig. 39.5 If in doubt, a marker (such as a Kirschner wire) may be placed.

Pitfalls

- Malpositioning of the screw may cause injury to surrounding structures.
- Medial and inferior placement may injure the exiting nerve root.
- Excessive medial angulation can also cause a dural tear.
- Overpenetration risks injury to the vascular and visceral structures anteriorly.
- Pedicle fractures may occur with aggressive use of the pedicle probe or by placement of an oversized pedicle screw without proper tapping.

40 Cortical Screw Fixation

Brian W. Su and Wellington Hsu

40.1 Description

Steffee et al described the force nucleus of the lumbar spine as the convergence point of the transverse process, lamina, and inferior facet with the pars, the superior facet, and the pedicle. As the basis for cortical screw fixation, this point provides cortical bone that does not become deformed in the setting of degenerative disease (▶ Fig. 40.1).

40.2 Key Principles

The pedicle is located medial to the midlateral pars 23%, 29%, and 36% of time from L3 to L5, respectively (▶ Fig. 40.2). As the initial starting point for a cortical screw, the ideal path enters the cortical bone at the pars and traverses the pedicle from a medial to lateral direction.

40.3 Expectations

Traditional open lumbar pedicle screw placement requires significant lateral dissection and exposure of the facet joint, pars, and transverse process. Because cortical screws have a medial to lateral trajectory, less muscle dissection is required. In biomechanical studies, there was noted a 30% increase in axial pullout strength with 4.5-mm cortical compared to 6.5-mm pedicle screws. Cortical screws allow for minimally invasive placement and equivalent biomechanical strength when compared to pedicle screws.

40.4 Indications

Cortical screws are used for posterior fixation during lumbar fusion procedures. They can even be used in the setting of a decompressive laminectomy if a fusion is required. The medialized head location allows for bone graft placement for a posterolateral and/or facet fusion. Cortical screws can also be used to supplement anterior, lateral, or posterior interbody fusions. Even in the setting of a TLIF (transforaminal interbody fusion) where the facet joint is sacrificed, cortical screws can be used with an entry point that is superior to the laminar resection required for a TLIF. Because less anatomical exposure is required, cortical screws are particularly useful in obese patients. Cortical screws are surrounded by higher density bone as demonstrated in cadaveric studies. Finally, osteopenic patients are also good candidates for cortical screw fixation as the pars is less affected by decreasing bone density when compared to the cancellous pedicle.

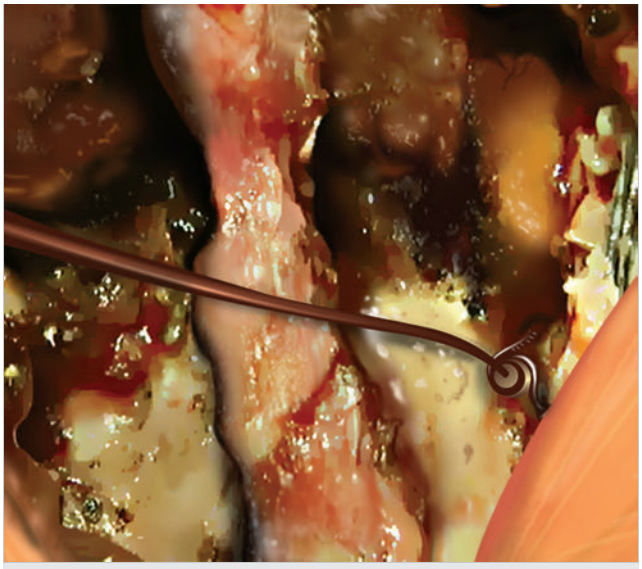

Fig. 40.1 Midlateral pars.

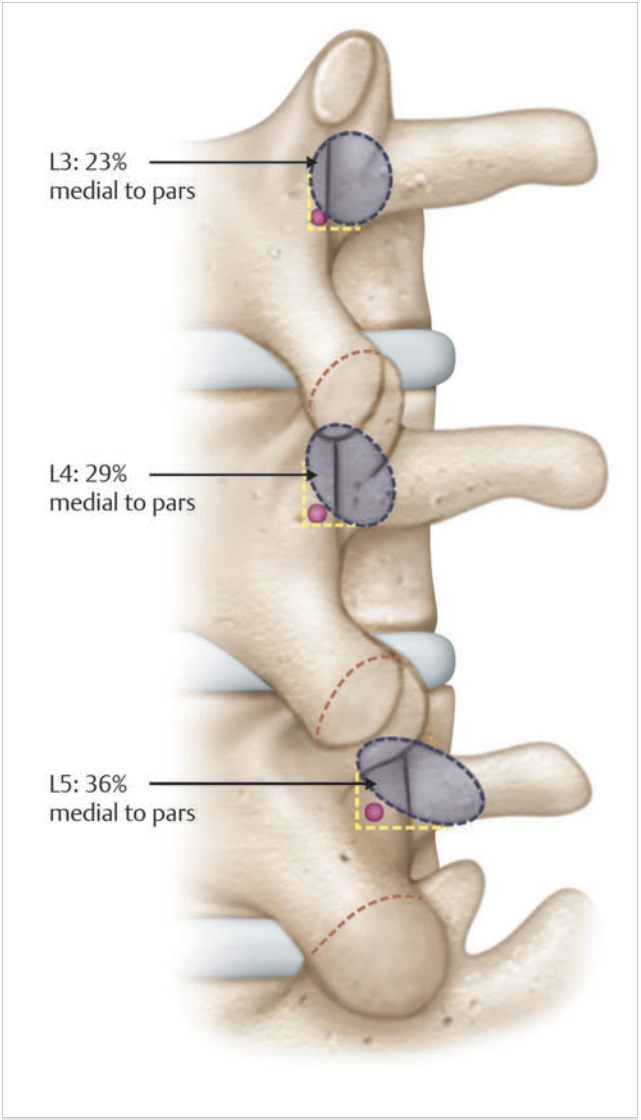

Fig. 40.2 Relationship of the medial pedicle to the midlateral pars. Cortical screw starting point (red) on the anteroposterior view relative to the medial and inferior border of the pedicle.

40.5 Contraindications

- Clinical contraindications are relative and include longer constructs (> three levels) and multilevel scoliosis or kyphosis correcting procedures requiring multiple osteotomies.
- Absolute contraindications include a congenital pars defect, lack of cortical bone at the pars secondary to a wide decompression, and iatrogenic pars fracture.
- Relative contraindications include a narrow or medialized pars and congenitally small pedicles. Narrow pedicles can lead to medial pedicle wall violation as the screw traverses the pedicle from medial to lateral after it enters the pars.

40.6 Special Considerations

Fixation of the sacrum in the setting of a cortical screw construct requires placement of an "up and out" alar screw. The starting location of this screw is medial and inferior when compared to a traditional sacral pedicle trajectory. It should be noted that this placement does not typically offer the same insertional torque as a lumbar cortical screw because of the lack of a cortical pars at the sacrum.

Because the pars is identified more medial at cephalad levels, caution should be used when placing cortical screws particularly at L1, as there may not be enough cortical bone medial to the medial pedicle wall. In addition, pedicle widths become smaller with cephalad levels that increase the likelihood that the screw penetrates the canal medially.

40.7 Special Instructions, Positioning, and Anesthesia

The patient is placed in the position prone on a radiolucent Jackson table using either chest/hip pads or a Wilson frame. Fluoroscopy is recommended to aid in obtaining the proper screw trajectory and final screw placement. A true anteroposterior (AP) view of the vertebral body is critical; typically L4 and L5 require a Fergusson view.

40.8 Tips, Pearls, and Lessons Learned

- Exposure of the corner where the pars meets the inferior aspect of the transverse process can be useful to help determine the starting point. The starting point will be on the pars at or below the inferior aspect of the transverse process. This point should be confirmed with AP and lateral fluoroscopy.
- To prevent skiving, the starting point should be made with the hand perpendicular to the spine and should be a 2-mm-deep divot. Once the starting point is made, the bur (with an AM-8 tip) or drill with a 25-mm length is typically reoriented in a 10-degree lateral and 30-degree cephalad trajectory. The screw is typically drilled and inserted under lateral fluoroscopy.
- Because the cephalad screw head has the potential of impinging on the adjacent facet joint, its starting point should be 1 to 2 mm more caudal to prevent the screw head from damaging the facet. In addition, the cephalad screw should be left a few millimeters proud to avoid damaging the cephalad facet with the rod.

40.9 Difficulties Encountered

- The caudal screw is placed in an up and out direction, which may require extension of the skin incision inferiorly.
- For the treatment of a degenerative spondylolisthesis, the cephalad cortical screw is often deeper to the caudad one, making the rod placement challenging. In this situation, we recommend using a slightly longer screw (e.g., 30 or 35 mm) at the cephalad level and leaving it proud to facilitate this.
- Orienting the screw laterally may be difficult secondary to the spinous process medially. Resection of the interspinous ligament and a portion of the spinous process may be necessary for screw placement.
- Many techniques call for the screw trajectories to be created prior to the laminectomy or interbody work. Performing an interbody fusion following screw placement is difficult because of the proximity of the caudal screw head to the disk space. Posted cortical screws with detachable tulip heads can be used in this situation. After creation of satisfactory screw holes, associated laminectomy and interbody work can be performed, followed by screw placement at the end.

40.10 Key Procedural Steps

- A standard subperiosteal midline exposure of the lumbar spine is performed. Compared to the incision for pedicle screws, the incision is slightly smaller and more inferiorly placed to allow for placement of the caudal screw. The facet capsule adjacent to the cephalad screw should be preserved. It is critical to expose the lateral pars at each level to be instrumented. Dissection lateral to the pars or facet joint is not necessary. Osteophytes from the facet at the fusion level can often overgrow and obstruct the pars of the cephalad

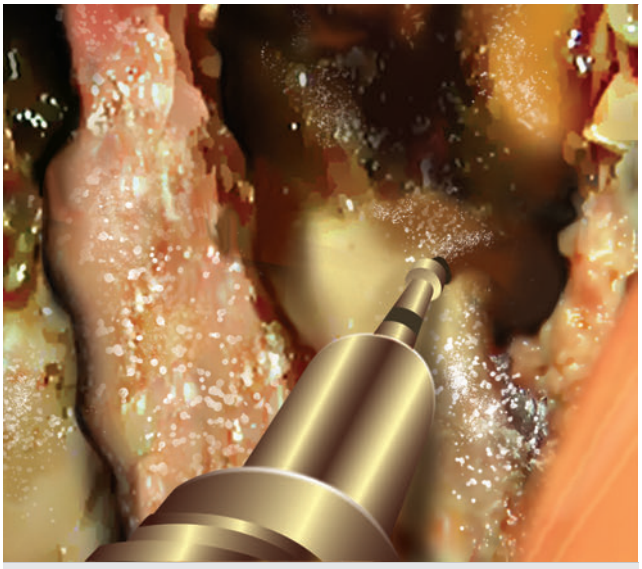

Fig. 40.3 Creating the starting point with an AM-8 acorn-tip bur.

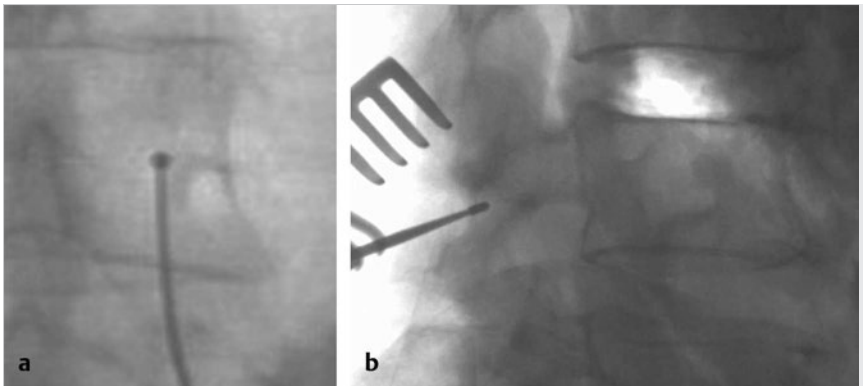

Fig. 40.4 Starting point on the (**a**) anteroposterior and (**b**) lateral views.

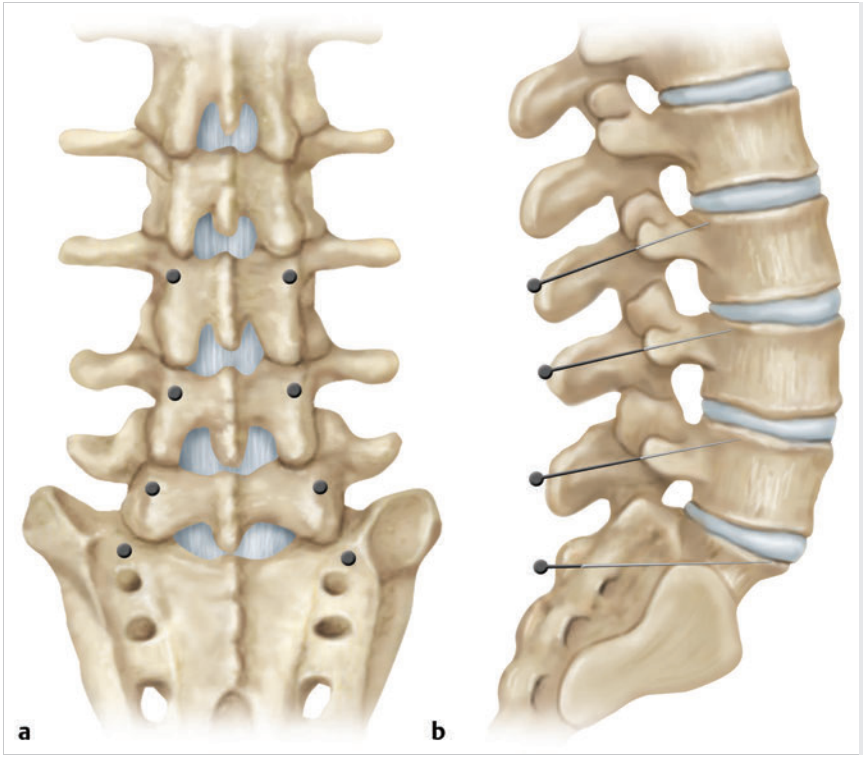

Fig. 40.5 Diagram of starting points on the (**a**) anteroposterior and (**b**) lateral views.

vertebrae. A rongeur should be used to resect the osteophytes until the lateral pars is clearly identified.

- The starting point is on the pars and is within the space delineated by an area lateral to the medial pedicle and superior to the inferior wall of the pedicle (▶ Fig. 40.2). A small 2-mm-deep starting point is made with a 3-mm acorn-tip (AM-8) bur (▶ Fig. 40.3). The tip of a small Caspar-type pin can be placed in each starting point as a marker for the starting point and trajectory. This location is then verified on the AP and lateral fluoroscopy view (▶ Fig. 40.4).
- Once the pilot hole is created, the drill is reoriented and the entire path of the screw is then drilled with an up and out trajectory. This is performed with either the 3-mm acorn-tip bur or a 3.5 mm drill. Tapping or pistoning of the bur or drill is useful to allow for tactile feedback through the pedicle. In the sagittal plane, the greatest angle in the craniocaudal direction should be used. In the axial plane, the drill should be directed 10 degrees laterally (▶ Fig. 40.5). The bur is then advanced 30 mm on lateral fluoroscopy from the inferior to superior portion of the pedicle, ensuring that the drill does not penetrate the superior end plate of the cephalad level.
- A ball-tip probe is then used to verify that there are four walls to the drilled hole (▶ Fig. 40.6). Once the length (20–35 mm; typically 25 mm) and width (4.0–5.5 mm; typically 5.0 mm) of the screw is determined, line-to-line tapping is performed with a fine- (cortical-) thread tap along the entire length of the screw. The hole is then reprobed and the screw inserted (▶ Fig. 40.7). It is not unusual for a cortical screw to have as much or more insertional torque than a traditional pedicle screw. Rods are then placed in standard fashion ensuring that the proximal rod does not impinge on the cephalad facet (▶ Fig. 40.8).

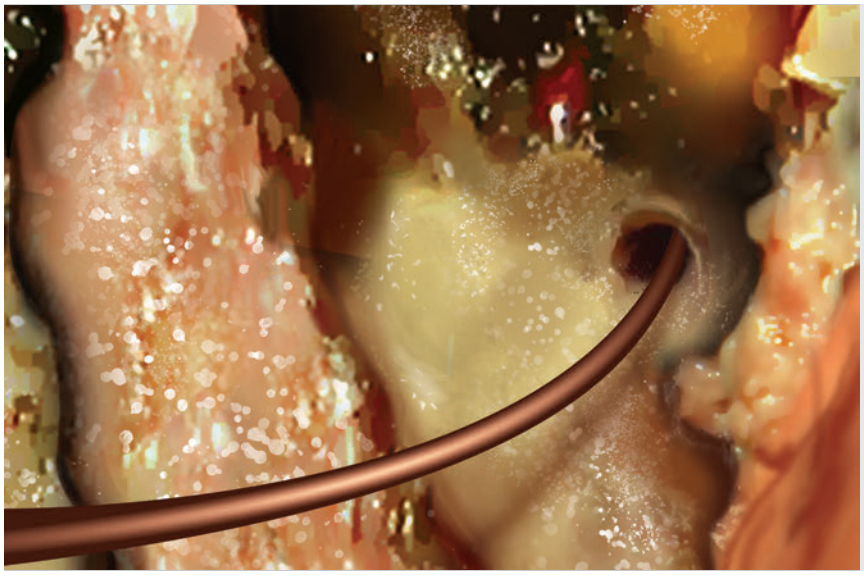

Fig. 40.6 Ball-tip probing the hole ensuring that there are four walls. The dangers are medial to the hole (spinal canal) and inferior to the hole (exiting nerve root).

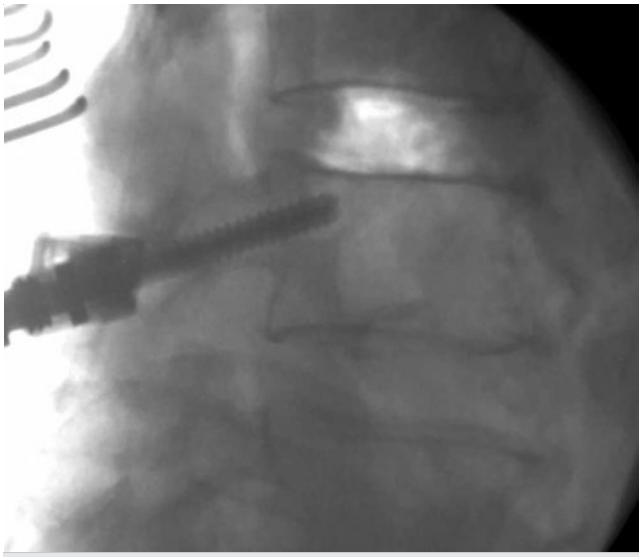

Fig. 40.7 Ideal screw position.

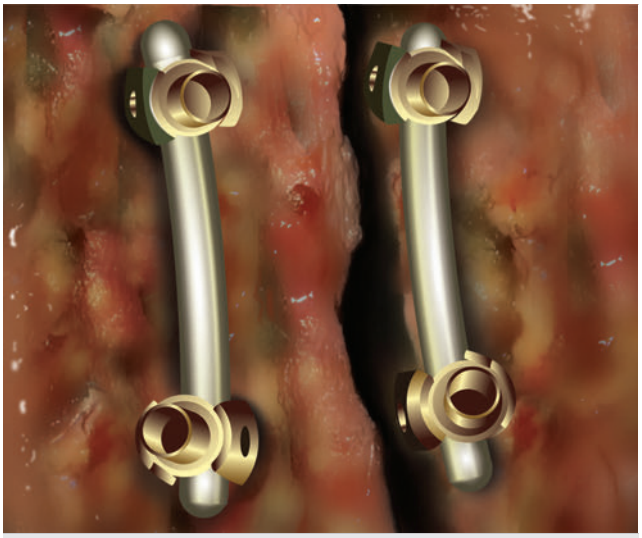

Fig. 40.8 Final construct. Note the medial location of the rods.

40.11 Bailout, Rescue, and Salvage Procedures

- If a cortical screw cannot be placed, a pedicle screw can be used to salvage the construct. It should be noted that cortical screws can be difficult to connect to adjacent pedicle screws secondary to the medial tulip-head location of cortical screw and the lateral location of the pedicle screw.
- If the pars becomes too narrow and a cortical screw cannot be placed at the caudal level, another alternative is a transfacet pedicle screw. This screw is placed with the starting point being at the superomedial corner of the caudal pedicle entering the superior articular process of the caudal facet. The screw traverses the hard subchondral bone of the superior articular process and enters the pedicle from a medial to lateral position (down and out). It is our experience that this screw has good insertional torque and can be placed as an alternative to a traditional cortical screw. Caution should be used when planning the starting point as the tulip head will be in close proximity to the cephalad cortical screw.
- If the screw path is significantly lateralized, biased angle polyaxial cortical screws may prove to be useful for rod attachment.

Pitfalls

- The potential for iatrogenic neural injury from a cortical screw includes the spinal canal medially and exiting nerve root inferiorly.
- The entry site of the screw is made of hard dense cortical bone and should be created with a bur and not a gearshift. If the surgeon prefers, a straight gear shift can be used through the pedicle once a bur or drill has created a cortical tract. Lateral fluoroscopy should be used to ensure that the gearshift is not advanced too deep into the adjacent cephalad disk space.
- Tapping line to line (5.0-mm tap for a 5.0-mm screw) along the length of the screw is critical. Cortical bone can be prone to fracture if a larger diameter screw is placed in a hole that is not tapped line to line.
- It is critical to perform the decompression and interbody work after creating the screw tract. Preservation of a minimum of 3 mm of pars between the tapped hole and laminectomy resection is required.

41 Transforaminal and Posterior Lumbar Interbody Fusion

Virgilio Matheus and Todd Francis

41.1 Description

Transforaminal lumbar interbody fusion (TLIF) evolved from the more medial posterior lumbar interbody fusion (PLIF) approach as a way to decrease the amount of dural retraction needed to reach the interbody space. Both approaches provide access to the interbody space and allow the surgeon to simultaneously instrument the anterior and posterior spine from a posterior-only approach. The PLIF, however, requires a bilateral medial approach and significant dural retraction, whereas the TLIF requires minimal retraction of the dura and nerve roots. The TLIF approach also provides a much more thorough unilateral (and perhaps bilateral) foraminal decompression.

41.2 Key Principles

Instrumentation of the anterior column restores spinal alignment and corrects deformity, increases fusion rate through greater bone–implant interface and load-sharing between the anterior and posterior instrumentation, and facilitates foraminal decompression directly and indirectly. The use of static or newer expandable cages allow for restoration of disk-space height tailored specifically for each patient.

41.3 Expectations

- Restoration of lumbar lordosis
- Correction of deformity
- Neural decompression
- Increased fusion rate when combined with a posterolateral intertransverse process fusion
- Potential decreased incidence of pseudarthrosis when performed at the end of long constructs due to enhanced support of the anterior column and load sharing of anterior and posterior instrumentation.

41.4 Indications

- Correction of coronal and sagittal plane deformity
- Isthmic and degenerative spondylolisthesis
- Back pain associated with recurrent disk herniation
- For enhanced support or adjacent segment disease at the end of a long fusion
- Consider as an alternative to posterolateral intertransverse process fusion in patients with elevated risk of developing pseudarthrosis (smokers, previous radiation, revision surgery with significant scarring over the posterolateral region)

41.5 Contraindications

There are definitive and relative contraindications, which should be weighted by the surgeon's level of expertise:

- Severe osteopenia
- Pre-existing end plate destruction (from osteomyelitis, for example)
- Blood dyscrasia
- Active infection
- Nerve root anomalies
- Severe fixed deformities
- The presence of the conus medullaris at the level of intended surgery (applies mainly to PLIF)

41.6 Special Considerations

Planning should include preoperative weight-bearing and dynamic radiographs of the lumbosacral spine. A magnetic resonance imaging (MRI) or a computed tomography (CT) myelogram must be obtained for understanding, complementing, and comparing the anatomy reflected on the radiographs. These studies will serve to better plan the surgical approach regarding side, pedicle size and orientation, nerve root location, and disk-space height. If unilateral facetectomy is planned, this should always be performed on the most symptomatic side unless contraindicated. In very specific cases of diskogenic pain, diskography is useful in determining the level of the pain generator; the clinician ordering this study must follow very selective criteria due to its controversial utility.

41.7 Special Instructions, Positioning, and Anesthesia

The patient should be placed prone with a decompressed abdomen on a radiolucent bed (such as a Jackson table). For long multilevel cases consider slight reverse Trendelenburg positioning plus a head fixation device (tongs/pins) to prevent prolonged pressure over the orbits decreasing the likelihood of retinopathy. A leg sling should be used when performing exposure involving the caudal most segments to facilitate exposure. Consider neurophysiologic monitoring (electromyography [EMG] and somatosensory evoked potentials [SSEPs]) during insertion of transforaminal grafts and cages as well as during cage expansion to help detect retraction injury to the exiting or traversing roots. Consider use of intraoperative blood salvage devices in cases with a high risk of significant blood loss or prolonged operative time.

41.8 Tips, Pearls, and Lessons Learned

In the PLIF, a complete laminectomy or bilateral hemilaminotomies with medial facetectomies is performed (▶ Fig. 41.1). In the TLIF, either unilateral or bilateral complete facetectomies should be performed for ideal exposure. In a TLIF, a medial unilateral hemifacetectomy may be performed and still allow for adequate exposure. Although this may limit working angle and visualization a bit, this method can bolster postoperative fusion.

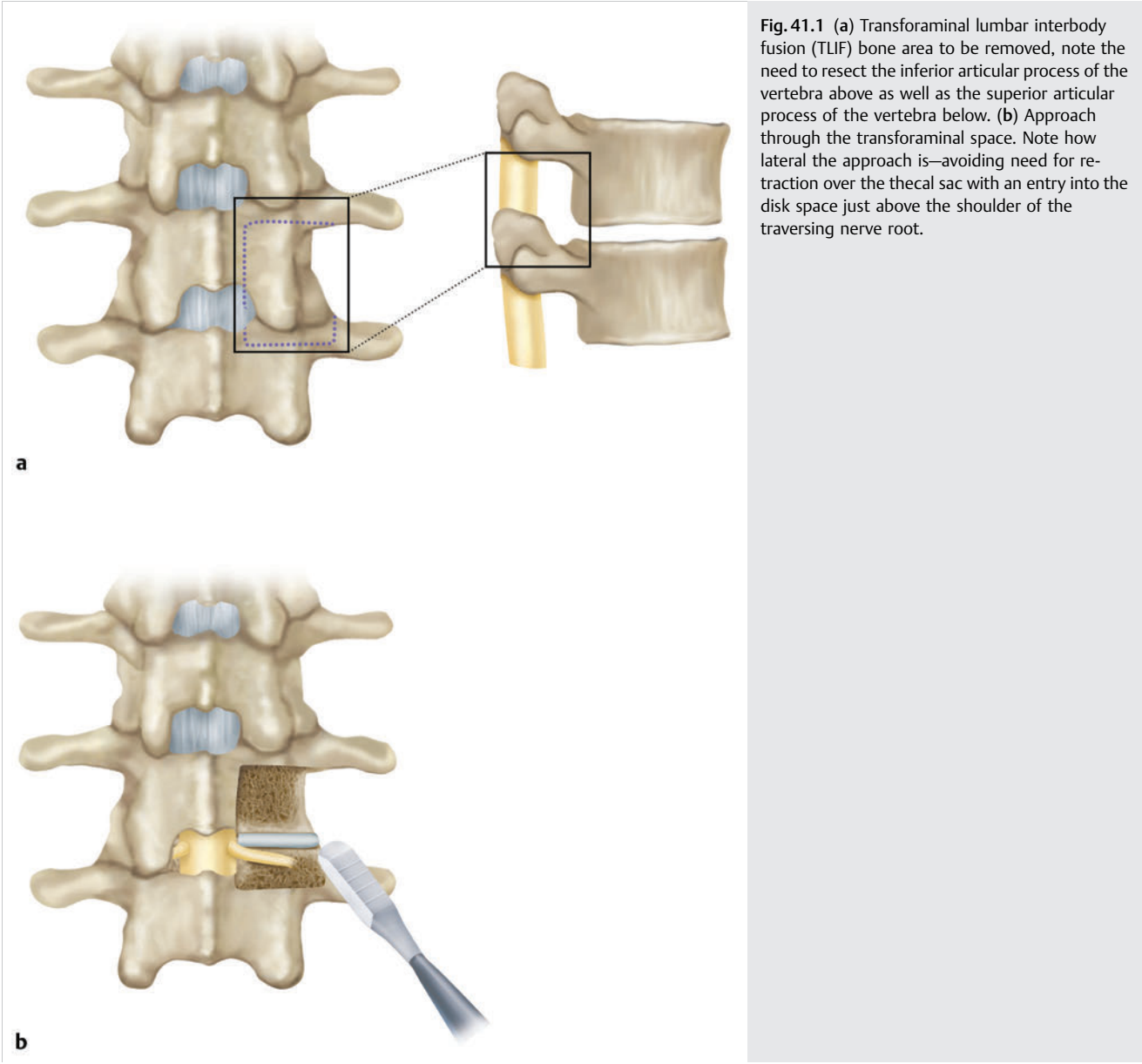

Fig. 41.1 (**a**) Transforaminal lumbar interbody fusion (TLIF) bone area to be removed, note the need to resect the inferior articular process of the vertebra above as well as the superior articular process of the vertebra below. (**b**) Approach through the transforaminal space. Note how lateral the approach is—avoiding need for retraction over the thecal sac with an entry into the disk space just above the shoulder of the traversing nerve root.

Before commencing with the facetectomy, it is imperative to identify the location of both the cephalad and caudad pedicles. Typically, this is done with a Woodson or Penfield elevator inserted medially underneath the laminar defect. During the facetectomy (especially while removing the superior articulating process), it is advisable to leave this instrument in place to protect the exiting and transiting roots from potential damage from the osteotome or drill. For the purpose of the facetectomy, the inferior articular process of the cephalad most vertebra is resected commonly with a small osteotome or a high-speed drill to preserve autograft material. The following step includes resection of the superior articular process of the caudal vertebra opening completely the foraminal space (▶ Fig. 41.2). The opening can be extended with Kerrison rongeurs from the bottom of the cephalad pedicle to the top of the caudal pedicle with careful attention not to breach these structures. If the facetectomy is performed properly, the exiting root will not be visible as it hugs the superior pedicle as it travels underneath the pars. Pedicle screws are typically inserted at this time. Temporary holding rods are placed either contralaterally or bilaterally, and the pedicles are distracted. Ipsilateral holding rods typically do not interfere greatly with the TLIF approach and can help to increase amount of distraction achieved and decrease the force placed on the contralateral pedicle screws during distraction. Care should be taken not to place excessive distractive force on the pedicle screws to prevent pedicle fracture.

A critical step of the surgery is achieving a thorough diskectomy; for this purpose, a wide variety of instruments including rongeurs, curettes, chondrotomes, and specialized shavers with and without angulation should be combined to achieve an extensive resection of disk and cartilaginous end plate (▶ Fig. 41.3). Often end plate osteophytes can be present, which can be easily resected with a small chisel or box osteotome to provide a larger entry. Square annulotomy with a scalpel should be performed with attention to protecting the surrounding

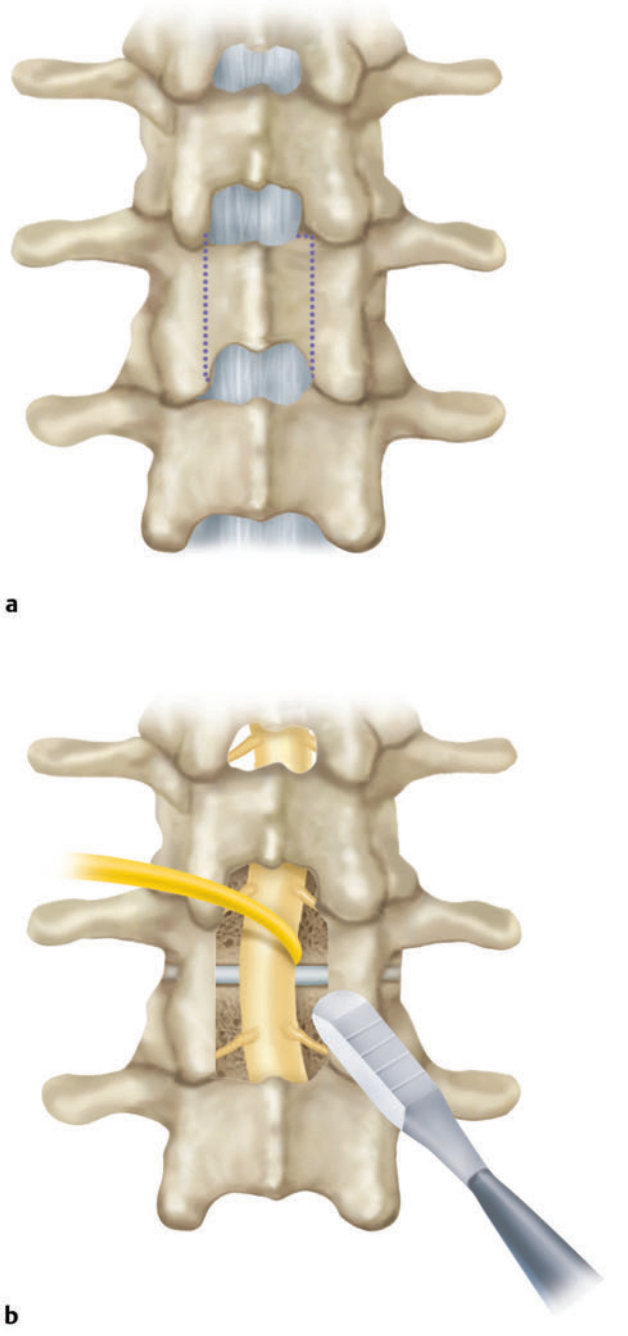

Fig. 41.2 (**a**) Posterior lateral interbody fusion (PLIF) bone area to be removed and (**b**) approach through the lateral recess of the central canal. Note that due to the medial entry into the disk space, retraction over the thecal sac is often needed.

neural structures. Distraction can be achieved by sequential dilatation using bullet distractors or lamina spreaders. Adequate distraction is more crucial for TLIF rather than for PLIF procedures. During PLIF, annulotomy and diskectomy are carried out similarly to the TLIF with extra attention to avoid injury from retraction of the thecal sac. During a TLIF diskectomy, it is important to ensure adequate contralateral diskectomy to guarantee a larger fusion surface area (▶ Fig. 41.4). Careful attention should be paid not to breach the end plates or the anterior anulus during diskectomy. This may potentially lead to graft subsidence and vascular injury.

Multiple interbody graft choices are available, including structural allografts, titanium mesh cages, threaded cages, carbon fiber spacers, and polyetheretherketone (PEEK) spacers. Most of these have a variety of shapes (bullet, rectangular, curved), plating angulation (parallel vs. lordotic), and expansibility options (cages). Regarding expandable cages, the surgeon must be aware of the graft's measurements when completely closed as well as at its maximal expansion point. Expansion can also be achieved through different mechanisms (stackable, parallel, vertical) all of which offer similar mechanical advantages and disadvantages. It is important to remember that whatever graft you place inside the expandable cage, the graft content will not be as voluminous once the cage is expanded to its maximal extent. This may require repacking (if feasible) after expansion. Positioning of the cage in a central and anterior localization will provide maximum lordosis, especially after compression is applied between the pedicle screws prior to securing the rods in place (▶ Fig. 41.5, ▶ Fig. 41.6).

41.9 Difficulties Encountered

Anticipation is the key to success in these procedures. Encountering significant bleeding during these procedures is not uncommon. Meticulous and judicious use of bipolar cautery in the foraminal space will prevent continuous bleeding during the diskectomy. If unable to achieve adequate intervertebral distraction, consider placement of a nonstructural graft such as cancellous bone chips.

41.10 Key Procedural Steps

- For a PLIF procedure, it is highly recommended to perform a wide laminectomy with medial facetectomy to provide space for thecal sac mobilization during the interbody portions of the technique. In a TLIF procedure, a wide variety of lamina resection options exist (for example, wide laminectomy, hemilaminectomy, hemilaminotomy with or without preservation of spinous process and ligaments). This decision may be based on the presence of underlying central canal stenosis, level of comfort with a specific technique, or level of confidence on achieving a thorough diskectomy through the chosen approach. The TLIF procedure requires the removal of part of or the whole facet complex; for this purpose, an osteotome or a high-speed drill can be used to transect the inferior articular process just caudal to the superior pedicle. Following this step, the surgeon should free the ligamentum flavum from the remaining exposed superior articulating process after which transection of the latter should be perform with an osteotome or drill just above the caudal pedicle. During facetectomy, it is advisable to protect underlying foraminal structures by placing a Woodson in the neural foramen. Completion of bone resection can be accomplished with Kerrison rongeurs. Utilizing osteotomes guarantees availability of more autograft material when compared to the use of a drill. In both procedures, thorough hemostasis of the epidural venous complex should be achieved with bipolar cautery.

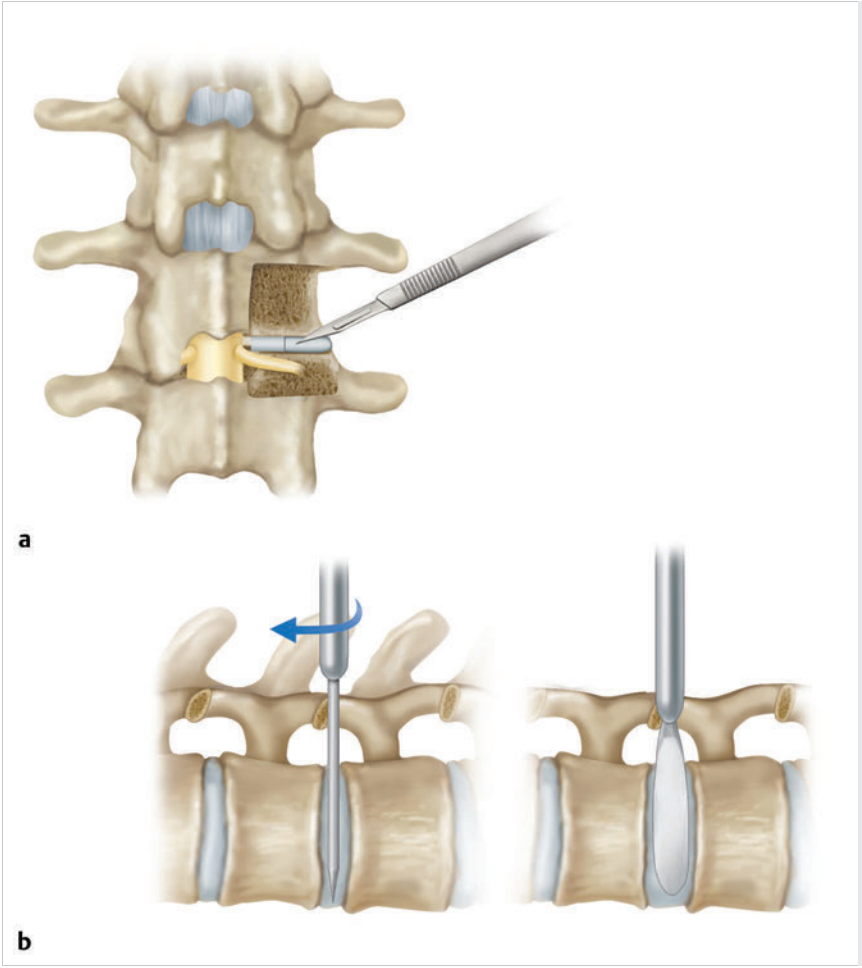

Fig. 41.3 **(a)** Boxed annulotomy performed with a scalpel, followed by a thorough diskectomy; similar for both procedures. **(b)** Space disk distractors are sequentially inserted on an increasing size order until adequate distraction is achieved. Note how the instruments must be parallel to the end plates at all times to avoid end plate breaching.

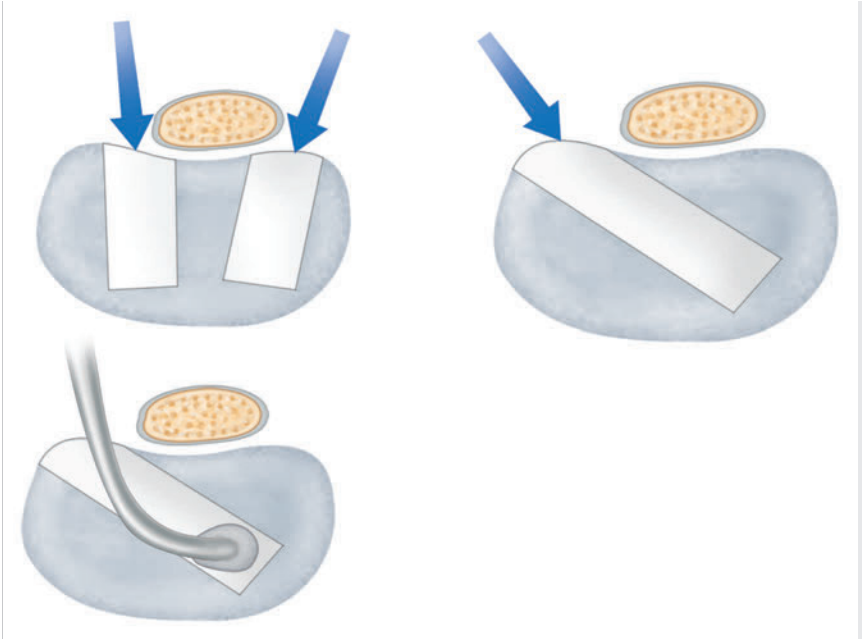

Fig. 41.4 Display of the disk space access obtained during (**a**) the posterior lateral interbody fusion and (**b**) the transforaminal lumbar interbody fusion procedures. **(c)** Note the need to utilize curved instruments to achieve a radical diskectomy due to the angle limitations for each procedure.

- For a PLIF procedure, careful medial mobilization of the thecal sac is performed intermittently from both sides to provide access to the disk space; special attention should be paid to the amount of retraction applied to the neural structures including the nerve roots. Extreme caution should be applied if working close to the level of the conus medullaris. In a TLIF procedure, gentle retraction, if needed, is applied to the shoulder of the traversing nerve root to facilitate exposure to

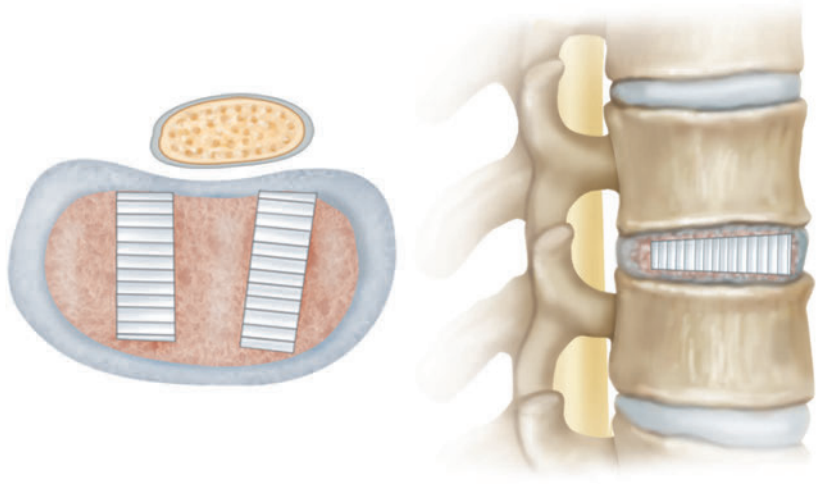

Fig. 41.5 Final position for the interbody cage/structural graft during a posterior lateral interbody fusion procedure. Note the presence of abundant morselized graft material lateral and posterior to the implants.

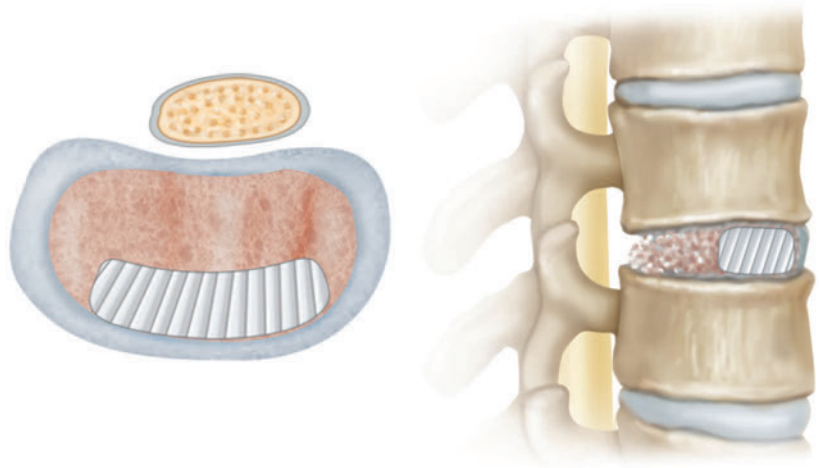

Fig. 41.6 Final position for the interbody cage/structural graft during a transforaminal lumbar interbody fusion. Note the need to confirm a centered anterior placement, which will facilitate compression of the posterior elements leading to better restoration of lumbar lordosis at this segment. Abundant morselized graft material must be place dorsal and lateral to this implant as well.

the disk anulus; the surgeon must be aware of any nerve root anatomical variations visualized on the preoperative imaging to avoid injury. This is especially required if a medial facetectomy is performed. If a complete facetectomy is achieved during a TLIF, then thecal sac retraction is generally not required.

- A sharp rectangular annulotomy is performed with a scalpel followed by a radical diskectomy performed with choice of instruments (curettes, shavers, graspers). Different types of interspace distractors can be used (paddles, dilators, etc.) in a crescendo manner to obtain adequate distraction through the diskectomy and end plate curettage. A temporary rod can be placed contralaterally to maintain the achieved distraction through the diskectomy. Avoid forcing interspace distractors that could result in breaching of the end plates precipitating graft subsidence. Refer to the intraoperative imaging to confirm the disk space angulation. Overdistraction could lead to neurologic injury or overloading of adjacent facet complexes.
- The contralateral disk space is packed with a small amount of graft followed by insertion of the structural graft or cage previously filled with grafting material. The graft or cage placement should be centered on the anterior disk space with the aid of fluoroscopy if direct visualization is not optimal. At this point, if the selected cage is expandable, the surgeon will proceed to expand it to its desired height, ideally with live fluoroscopy to avoid end plate damage or unplanned tilting of the cage during the expansion. The remaining graft material is carefully packed inside the expanded cage, on the ipsilateral side of the disk space and behind the structural graft. Lastly, pedicle screws are inserted if not previously done (surgeon's choice), gently compressed, and fixed with rods. Our choice is to also perform an intertransverse process fusion where feasible to increase the fusion mass surface.

41.11 Bailout, Rescue, and Salvage Procedures

In cases where (1) bleeding is so significant it prevents adequate visualization of the disk space, (2) violation of an end plate occurs, or (3) the surgeon is unable to achieve disk space distraction, it is highly recommended to remove or avoid placement of a structural graft and instead pack the interspace with

morselized nonstructural graft material. To assess for ventral compression of the thecal sac, gently feel with a curved blunt instrument (e.g., a Woodson elevator) for any bulges over the anterior longitudinal ligament. Final intraoperative imaging can detect suboptimal graft placement and occult end plate violations.

Pitfalls

- End plate violation
- Lateralization of the cage/graft
- Excessive bleeding from the epidural space
- Inability to distract the disk space
- Lack of parallel graft placement to the end plates
- Cage/ graft material bulging ventrally into the thecal sac

42 Guided Lumbar Interbody Fusion

Morgan P. Lorio and Jeffrey Guyer

42.1 Description

The guided lumbar interbody fusion (GLIF) or Guyer LIF is a single incision, dorsolateral, retroperitoneal, transpsoas interbody fusion achieved through a familiar prone position with a curvilinear portal. The GLIF allows for fluoroscopic-aided, tactile finger dissection assisted with neuronavigation, and direct visual docking confirmation. Prone access to the anterior column (first through fifth lumbar vertebrae) offers a circumferential, single-staged approach incorporating standard direct ARC portal approach with lumbar interbody fusion and standard decompression with 360-degree posterior fixation (▶ Fig. 42.1).

42.2 Key Principles

- The ARC Portal System (Alphatec Spine, Inc.) provides a curvilinear minimally invasive corridor to the prone lateral lumbar spine with GLIF technique.
- 360 or circumferential fusion is achieved with "no flip" (or repositioning); simultaneous 360-degree access to the prone spine is accomplished in "one trip" (one operative anesthetic, one operating room [OR] encounter).
- GLIF cage implant's external geometry resists migration due to its "all-weather tread." GLIF cage implant's internal capacious geometry is uniquely designed to hold bone graft and/or other biologics while maximizing anterior support engaging end plates and apophyses.
- Deployment of the convertible hinged lid achieves a direct line of sight via ARC Portal System's uniquely incorporated retractor. Direct visualization allows for docking or positional confirmation and neural injury avoidance.

Fig. 42.1 Arc Portal System docked against prone lumbar spine.

- ARC Portal System with GLIF is an efficient alternative access addition to the spine surgeon's armamentarium (**Video 42.1**).

42.3 Expectations

Unlike anterior lumbar interbody fusion (ALIF) or other lateral retroperitoneal approaches to the lumbar spine, GLIF offers several direct lateral fusion advantages by obviating the technical need to reprep or reposition in the OR or return to the OR for procedural completion (with GLIF, you may expect "no flip" or "one trip.") Econometric value through GLIF is thus validated with decreased OR time, decreased anesthetic time, and decreased hospital stay.

42.4 Indications

The GLIF surgical indications for anterior column lumbar fusion include symptomatic pathology involving the first through fifth lumbar vertebrae, including but not limited to the following: scoliosis, spondylolisthesis that can be reduced prone intraoperatively to grade 1, select fractures amenable to lateral transpsoas approach, segmental spinal instability associated with stenosis, diskitis, etc.

42.5 Contraindications

- Spondylolisthesis that cannot be reduced prone intraoperatively to grade 1
- Bilateral scarring that precludes retroperitoneal dissection from either side
- Systemic infection

42.6 Special Considerations

Osteoporosis impacts safe fluoroscopic targeting of the lumbar spine during GLIF. If the spine cannot be adequately visualized, then an alternative approach with GLIF abortion is prudent. The most important consideration is time spent to ensure the very best visualization (targeting)—keep the target in the very center of the fluoroscopic circle to avoid parallax errors.

Neuronavigation must be used for safe GLIF technique with the ARC Portal System. The neuromonitoring technician must work as part of the GLIF team keeping both the surgeon and anesthesiologist informed of their concerns, etc. The patient must be adequately relaxed at "two twitches." In general, an initial stimulated value of greater than 12 mAmps imparts confidence, and less than 8 mAmps bodes concern as subsequent final dilation may require GLIF abortion.

42.7 Special Instructions, Positioning, and Anesthesia

A Jackson table with sling works best with the GLIF/ARC Portal System. Bilateral prone position with wide surgical prep

ensures access from either side. Historically, the surgical aortic dissection technique has been easier from the left, rather than from fragile vena cava mobilization on the right. Dense anesthesia or "zero twitches" obviates the safety imparted by neuronavigation. Light anesthesia, however, may be worse in that at "four twitches" the patient may inadvertently move changing the relative position of the spine and disengage the docked portal's life-line anchor to the disk space. For that reason, the entire GLIF team must understand the procedure, maintain complimentary communication lines, and function as a team.

42.8 Tips, Pearls, and Lessons Learned

Careful consideration of the preoperative X-rays and either a good computed tomography (CT) myelogram or magnetic resonance imaging (MRI) is a bare-bones minimum radiographic screening that must be reviewed prior to surgery to template cage implant size, to plan docking position, and to circumnavigate visceral concerns. A very small vertebral morphology may push the position ARC Portal System anteriorly to necessarily avoid encroachment on the neural conduit.

L1/L2 and L2/L3 interspaces are relatively safe targeting if the genitofemoral nerve is not considered. Additionally, at the same levels it is important to appreciate and avoid the kidneys and not avulse or injure the renal pelvis blood supply or ureter. Therefore, prior kidney surgery may encourage approach to the contralateral side; fortunately, the prone position allows these vital organs to sag anteriorly away from the operative zone. Ribs may block an alternative access to these very same levels while providing rib graft material if desired.

The current initial dilator (D1) is 5 mm in diameter and the anterior tang is 6 mm in width. Thus, disk space collapse greater than this range is a relative contraindication for GLIF (smallest cage height is 8 mm). Serial distraction of the disk space is achieved with soft tissue release and/or the adjunct of "simultaneously" applied distraction via posterior segmental pedicle screw instrumentation and/or posterior element resection with decompression. The GLIF technique approach provides improved sagittal restoration. In that GLIF is accomplished prone, conversion to transforaminal interbody fusion (TLIF) remains a salvage option.

A high disk with a height of greater than 8 mm provides ample opportunity to maximize soft tissue release and to improve end plate preparation, ensuring successful fusion for the novice. Although the ARC portal provides for a direct line of sight, the initial targeting with the calibrated introducer requires a curvilinear approach to spatial analysis, which improves with the learning curve.

Psoas dissection prior to sequential dilation is from anterior to posterior with the surgeon's gloved finger or with a peanut or modified Penfield dissector. Sufficient time spent during this provisional soft tissue release facilitates subsequent neuronavigation, serial dilation, and docking. The L4–L5 level presents special challenges impacted by the geometry of the iliac wings. A high disk at L4—L5 above or at the intercrestal line is a reasonable target, and both left- and right-sided access should be considered fluoroscopically and/or clinically. The L3 nerve root may require extensive mobilization to serially dilate and dock at the L4–L5 disk. Lessons learned with L4–L5 in particular include patience with both neuronavigation and soft tissue dissection to create a "clear zone," avoiding iatrogenic neural injury with resultant thigh pain. Avoidance of neural injury (sensory or damaged/ diseased elements) may require both higher thresholds than 12 mAmps and monitoring of all possible effector muscles which is not without limitations.

42.9 Difficulties Encountered

The potential for neurologic complications at L4–L5 are real—in part due to portal footprint-induced stretch of the psoas muscle required to safely dock on the lateral aspect of the anterior lumbar spine. The GLIF technique with the ARC Portal System when properly done sweeps the psoas from anterior to posterior, while neuronavigating the psoas in a prone relaxed position rather than the stretched position encountered in lateral decubitus position associated with other lateral retroperitoneal transpsoas approaches. In a low-seated L4–L5 disk, the experienced GLIF surgeon may use the ARC portal as a lever arm against the pelvis, but this maneuver limits one's ability to simultaneously sweep the initial dilator from anterior to posterior with simultaneous neuronavigation using the calibrated introducer. If a safe or clear zone cannot be initially achieved at greater than 12 mAmps with the initial dilator then subsequent sequential dilation will fail. Deformity induces psoas contracture, spurs, and a less than favorable flush surface that may be circumvented with the adjunct of one or two obliquely placed bony fixation pins through the portal after the soft tissues are retracted further with modified Penfield and/or the posterior tang guide. If neuromonitoring results are borderline or docking is not ideal, then one must abort and proceed with TLIF or an old-fashioned posterolateral fusion (PLF). Remember all familiar salvage prone options remain with GLIF prone positioning.

42.10 Key Procedural Steps

42.10.1 Targeting

Prone positioning imparts laxity to the anterior column and psoas, which are integral to using the GLIF technique to full advantage. The spine stiffens with anterior column restoration; hence L4–L5 should be approached first to maximize access and to avoid direct iliac crest obstruction (L3–L4 is a best first single-level target for the novice). Curvilinear targeting requires that the targeted focus of surgery remain within the center of the fluoroscopic screen to avoid parallax errors. Although the initial dilator might be introduced by an accomplished hand alone, the calibrated introducer was developed to facilitate safe, reproducible instrument delivery to the targeted surgical site and is strongly recommended. The axial plane of the targeted disk should be perpendicular to the floor and fluoroscope. Lateral fluoroscopy is used to initially localize the operative level using a loaded and locked calibrated introducer with vertical pin contacting the patient's skin (▶ Fig. 42.2). The target is biased to the posterior third (or 40%) of the anterior column and is located using an anterior/posterior adjustment knob and subsequently locked with the craniocaudal locking knob. The vertical pin is exchanged for the initial dilator (D1). The swing of the calibrated introducer is then used to rotate D1 until it

Fig. 42.2 Calibrated introducer with vertical pin contacting the patient's skin.

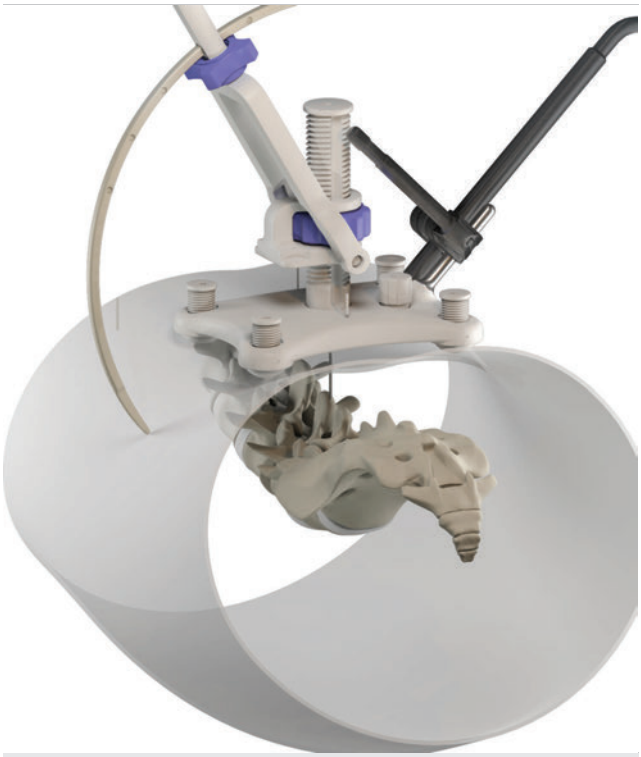

Fig. 42.3 The calibrated introducer delivering the initial dilator and defining the skin incision.

contacts the skin, which marks the approximate center of a 4-cm anterior/posterior incision through the skin and fascia (▶ Fig. 42.3). Gloved finger dissection to the subcutaneous tissue and muscle typically delineates a loss of resistance by the retroperitoneal space. Sweeping the peritoneal structures with gentle spreading dissection anteriorly is an important tip. Transverse process palpation then guides the fingers further anteriorly as the psoas muscle is palpated. With a finger placed over the tip of D1, the calibrated introducer is simultaneously used to swing D1 from its dorsolateral entry point safely through the retroperitoneal space, transpsoas, docking on the disk anulus. This is confirmed with fluoroscopy in the lateral plane first, and thereafter with additional anterior/posterior fluoroscopic viewing. Readjustments with the calibrated introducer are required to again improve on the posteriorly biased target; neuromonitoring is used at this point of the procedure. A sweeping maneuver with D1 may be required from the anterior third to the posterior third position to ensure an initial neurostimulation value of greater than 12 mAmps.

This initial targeting with neuromonitoring avoiding parallax is critical: Time spent optimizing targeting will save time ultimately and help ensure safe optimal implant delivery. The guidewire is then delivered through the cannulation of D1 while optimally monitoring the guide arm advancement with intermittent anterior/posterior fluoroscopy. Gentle levering of the calibrated introducer arm may be required to bisect the disk and to bypass anular osteophytic spurs when present. A surgical clamp may be useful for guidewire impaction to approximately 3.5 cm. The D1 is fully impacted into the intervertebral space using a provided impactor and mallet. The guidewire and calibrated introducer can now safely be retired. D1 placement anchors a fixed trajectory for subsequent serial dilatation. Tip: Maintain the position of D1 against the anulus as viewed in anterior/posterior fluoroscopy to prevent inadvertent detachment during the subsequent soft tissue dilation. Serial dilation is subsequently done with moistened dilator 2 (D2) and dilator 3 (D3) as they are gently manipulated towards the anulus as viewed in anterior/posterior fluoroscopy. The surgeon's finger is used as a soft tissue shoehorn along the perimeter of each dilator as necessary to ensure that soft tissue entanglement does not occur; this facilitates a flushed docking against the lateral wall of the spinal column. Satisfactory placement of both dilators (over anchored D1) is ensured when the fluoroscopic markers on D2 and D3 are superimposed on the anterior/posterior fluoroscopy and positioned satisfactorily so as to avoid neural conduit encroachment posteriorly.

42.10.2 Access: Anterior Tang Deployment

The ARC portal with activated GLIF illumination is delivered over D3 and fully seated against the lateral wall of the anterior spinal column and secured with gentle, level pressure to the table fixation arm. The anterior tang impactor is connected to the anterior tang and impacted into the anterior disk space under lateral fluoroscopic advancement. Anterior/posterior visualization is additionally crucial to navigate fixed angular deformity and to ensure perpendicular trajectory through the disk access. Anterior tang deployment provides a final life-line anchor to the spine and resists anterior translation of the portal, thereby protecting the great vessels avoiding life-threatening hemorrhage. The anterior tang impactor is then retracted

Fig. 42.4 Anterior tang deployment with a retracted ARC Portal System providing direct visualization.

from the portal and the dilators are removed as the convertible top of the ARC portal is opened with a toeing wrench that retracts and exposes the operative site (▶ Fig. 42.4). Direct visualization, inspection, and further meticulous preparation with Penfield dissectors is performed as residual soft tissues are mobilized away from the working corridor. With neuromonitoring, one must paint the surface of the anular work zone to map an electrical confirmation that corroborates the direct visual correlate of a "clear zone."

42.10.3 Posterior Tang Insertion, Bony Fixation Pin Insertion, Disk Preparation

The posterior tang guide is assembled through the curved portal with the handle in an unlocked position until fully seated. Compression of the handle guide locks and secures the posterior tang into the anulus as final soft tissue retraction is simultaneously achieved. The posterior tang provides a tactile safety corridor guide further ensuring safe trajectory while preventing inadvertent broach of the neural conduit during diskectomy. With the posterior tang deployed and neuromonitored bone fixation pins inserted through the portal, disk preparation begins.

Disk preparation can now safely be initiated with an adaptive annulotomy knife, anulus punch, or specialized boxed osteotome. Thereafter, specialized curvilinear pituitaries, curettes, rasps, and osteotomes may be used to repair the intradiskal space and end plates. A mechanized rotatory actuator with shaver blades and rotatory distractor attachments may expedite disk space preparation and provisionally template the same (▶ Fig. 42.5). Afterward, end plate trials with appropriate geometry are subsequently trialed. Controlled anular release on the contralateral side is performed almost as the very last step to

Fig. 42.5 Rotating actuator delivered through the ARC portal preparing the intervertebral disk space for fusion.

Fig. 42.6 ARC Portal delivery of a guided lumbar interbody fusion cage implant using impactor inserter.

ensure a palpatory tactile barrier wall while the intradiskal work is completed. The contralateral anulus is released and the residual disk plug is removed. Ultimately, the ARC portal is then used to deliver the impacting inserter with attached GLIF implant filled with graft material into the disk space (▶ Fig. 42.6). The GLIF implant is ideally positioned between the anterior and middle third of the disk space resting on the lateral apophyseal edges and maintaining bony contact throughout as reviewed on both anterior/posterior and lateral fluoroscopy; the ARC portal is collapsed and removed as the wound is closed in a layered anatomical fashion with nonabsorbable sutures used in the fascia of the muscle to avoid hernia.

42.11 Bailout, Rescue, and Salvage Procedures

A left-sided approach may very well be the safest from a historical dissection perspective from L1–L5 given that aortic dissection as performed is preferable over the inferior vena cava.

Coronal plane deformity, however, does not comply with ideal circumstances, although the concave side of the deformity allows for convergence; it additionally limits disk access, although theoretically optimizing release. Both convex docking and concave docking are considered with a prone GLIF approach. Safe GLIF is accomplished only with precise targeting, D1 disk engagement, and anchored ARC portal docking with anterior tang deployment.

If the disk cannot be targeted due to retroperitoneal safety concerns induced by the anatomical areas between the diaphragm above and the iliac crest below, then prone TLIF is and remains a rescue salvage procedure. Alternatively, the GLIF might be converted to a "mini open bailout" to address unforeseen complications. GLIF abortion is appropriate to avoid avulsion of the ureter or renal artery above L2 and/or L3 nerve root injury at the L4–L5 disk space level.

Pitfalls

- The initial trajectory chosen by the current GLIF beta-phase release is defined by blind soft tissue dilation augmented with neurostimulator use and accompanied by a steep learning curve.
- The L5–S1 interspace is not accessible by GLIF due to the iliac crest.
- Moreover, the L4 and L5 nerve root as well as the femoral and obturator nerves make prone curvilinear access with neuronavigation ominous even in the absence of an obstructing crest.
- Other alternative accepted approaches must be considered for L5–S1 if they are to be effectively coupled with the advantages of GLIF as described for levels L1–L5.

43 Spinous Process Plating

Tyson Garon, Kevin P. McCarthy, Gregory D. Schroeder, and C. Chambliss Harrod

43.1 Description

Lumbar fusion procedures have increasingly been performed for a variety of etiologies, including degenerative conditions, deformity, trauma, and tumors. Open lumbar pedicle screw placement traditionally involves an extensive wide dissection for exposure of the transverse processes to guide anatomical freehand screw placement as well as allow intertransverse fusion. Recently, minimally invasive fusion techniques have increased in popularity to accomplish arthrodesis, including transforaminal and lateral interbody techniques. Spinous process plating is a minimally invasive posterior fixation option that is combined with bone grafting to avoid the need for more extensive and challenging exposure with pedicle screw placement.

43.2 Key Principles

Adjacent segment pathology (ASP), including radiographic deterioration (RASP) and clinical symptomatic disease (CASP), has been associated with lumbar fusion procedures, particularly those augmented with posterior pedicle instrumentation. Exposure and placement of the most cranial screw often violates the cephalad facet capsule and joint, which is thought to increase both RASP and CASP. Spinous process plating (SPP) instrumentation is a less technically demanding, less-invasive instrumentation technique that decreases inadvertent injury to the cranial facet complex while providing stability for fusion. Single- or multiple-level posterior thoracolumbar spine fixation is possible. It is not indicated for stand-alone use and must be used in conjunction with bone grafting and anterior interbody grafting or additional posterior pedicular fixation.

43.3 Expectations

Studies have shown that spinous process plating results in decreased operative time, blood loss, radiation exposure, and soft tissue dissection when compared to pedicle screw fixation. The technique should not be used as a stand-alone construct without adjunctive bone grafting and is still debatable in multilevel pathology. Due to its large fixation footprint that rigidly attaches to the broad surface of adjacent spinous processes, fractures are, in general, less common than with some posterior nonfusion interspinous process devices.

43.4 Indications

Indications are still controversial and are currently being defined and refined and vary based on surgeon experience. Single-level posterior fixation in the thoracic and lumbar spine for the treatment of degenerative disk disease, grade I degenerative spondylolisthesis (▶ Fig. 43.1), and stenosis has been advocated.

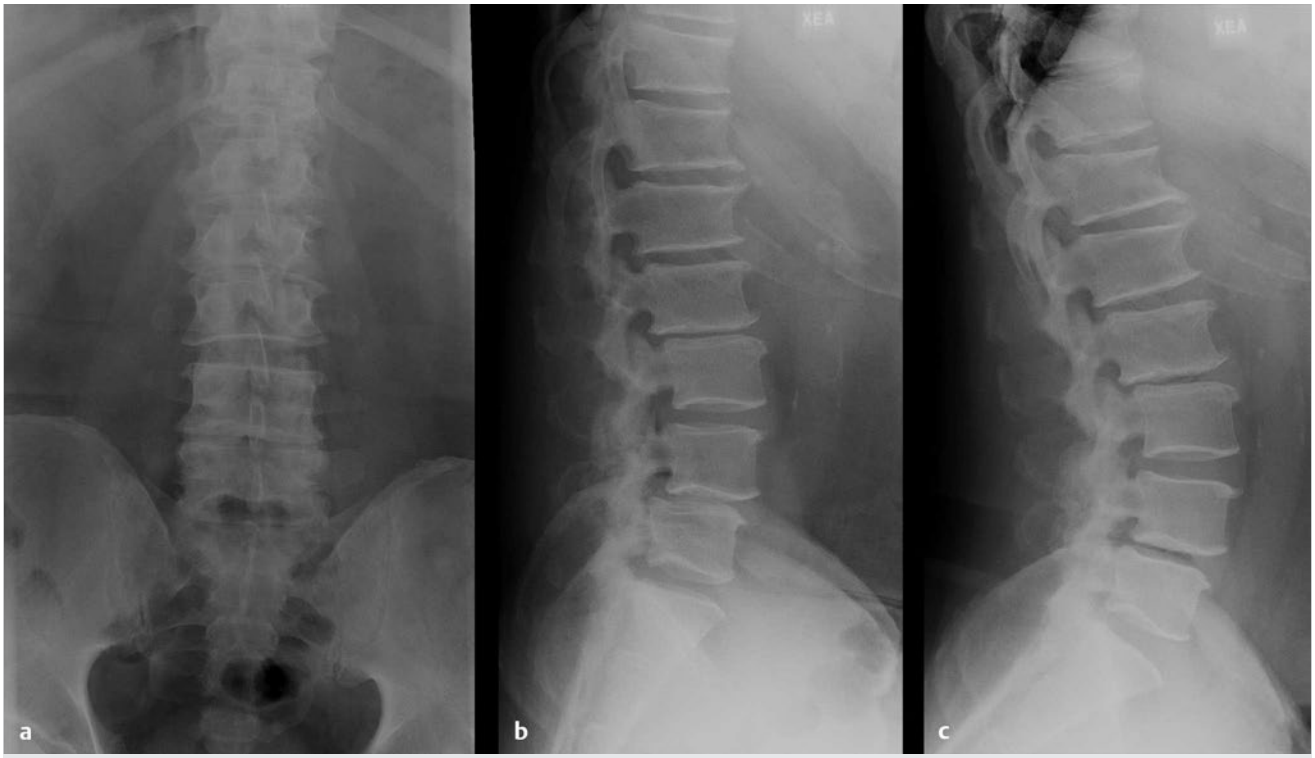

Fig. 43.1 **(a)** Anteroposterior, (**b**) flexion, and (**c**) extension lateral radiographs demonstrating an ideal candidate with a grade I degenerative spondylolisthesis.

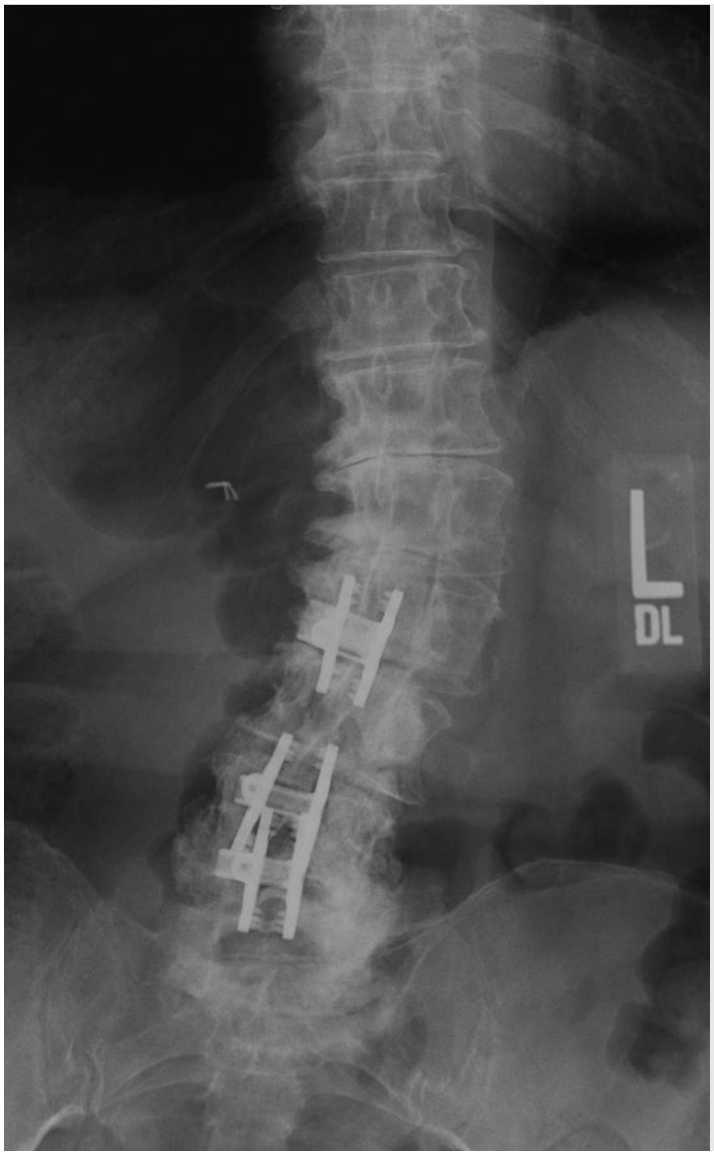

Fig. 43.2 Anteroposterior radiograph demonstrating moderate degenerative lumbar scoliosis too severe for posterior spinous plating techniques.

Recurrent disk herniation requiring facetectomy and segmental destabilization is also a relative indication.

43.5 Contraindications

Patients with severe rotational, coronal (▶ Fig. 43.2), or sagittal plane deformities, grade II or greater instability, isthmic spondylolisthesis, inadequate or dysplastic posterior elements due to prior laminectomy are contraindicated for this device. Relative contraindications include severe osteopenia or osteoporosis, infection, and multiple-level pathologies. SPP techniques should not be used without bone graft or additional anterior interbody support or posterior internal fixation.

43.6 Special Considerations

Carful initial preoperative radiographic evaluation with radiographs including standing lateral (flexion, neutral, and extension), lumbosacral spot views, and full-length 3-foot lateral and posteroanterior views are essential in understanding global spinal alignment, deformity reducibility, and local pelvic parameters (pelvic incidence, sacral slope, pelvic tilt, slip angle). Magnetic resonance imaging (MRI) is invaluable for fully evaluating sites of neural compression, whereas computed tomography (CT) is excellent at quantifying bony structures including planning of instrumentation, decompression, or possible osteotomies, and evaluating bone stock. Dual-energy X-ray absorptiometry (DXA) scans are helpful in diagnosing osteopenia and osteoporosis. Preoperative treatment of metabolic disease with the guidance of endocrinologists can markedly improve bone stock and possibly decrease risk of fracture, pseudarthrosis, and revision surgery. CT myelograms are useful in evaluating bony and neural anatomy when MRIs are contraindicated. CT myelograms are also indicated after prior spinal surgery (particularly when prior instrumentation may distort MRIs). Morbidly obese patients, revision cases, and suboptimal bone quality create more challenging environments.

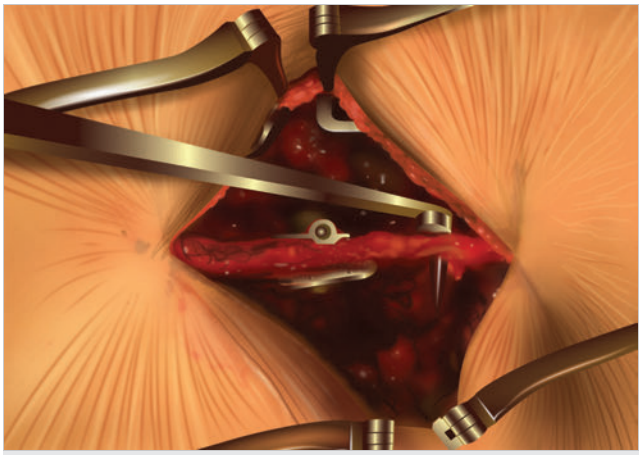

Fig. 43.3 Intraoperative image demonstrating initial awl placement.

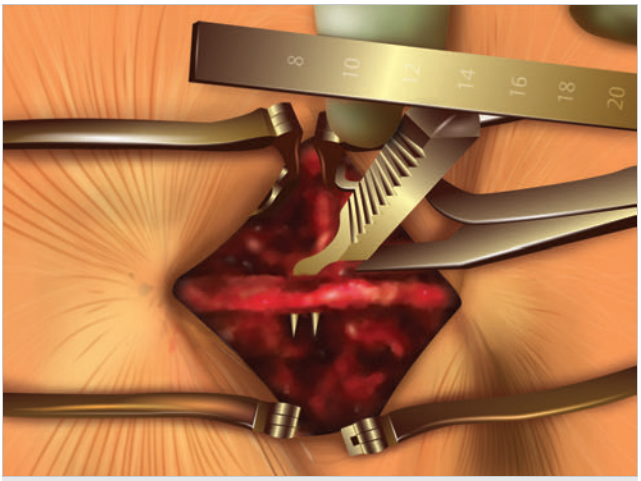

Fig. 43.4 Intraoperative photograph demonstrating distracter placement.

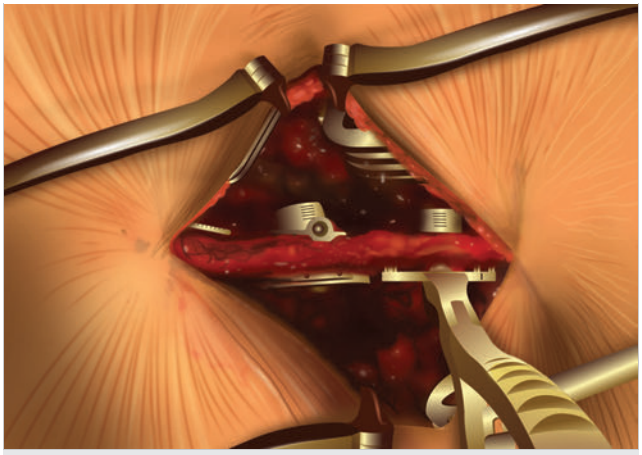

Fig. 43.5 Intraoperative photograph demonstrating placement of first plate.

43.7 Special Instructions, Positioning, and Anesthesia

Spinous process plating is performed through an open posterior approach. The patient is placed in the prone position typically on a Jackson table (to induce lordotic alignment), and a posterior midline approach is performed with preservation of the supraspinous ligament if possible. Utilization of the appropriate size implant is necessary to avoid malposition, implant loosening, and spinous process fracture. This is magnified when placing multiple devices. Biomechanically, SPP resists flexion and extension with construct stability weaker in torsion and lateral bending than pedicle screw constructs. Additional dissection or incisions may be necessary to place additional hardware or bone graft materials.

43.8 Tips, Pearls, and Lessons Learned

Grade I L4–L5 degenerative spondylolisthesis associated with lumbar stenosis is the most common indication for SPP (▶ Fig. 43.1). A standard midline incision is utilized to allow easy bilateral access to the posterior elements. A decompression can be indirect via distraction of the posterior elements with an increase in the foraminal region with simply placement of the device (much like prior interspinous process devices such as X-stop [Medtronic]) or additional direct decompression can be performed. After decompression is performed with laminotomies, foraminotomies, facetectomies, and diskectomies as needed via standard techniques, attention is turned to SPP reconstruction. An interspinous window is created and widened with the use of an awl (▶ Fig. 43.3). A distracter can then be spread to tension and estimate trial size (▶ Fig. 43.4). Trial sizers can then be fitted between the spinous processes followed by placement of the device (▶ Fig. 43.5), which mates with its appropriate counterpart on the contralateral side (▶ Fig. 43.6). Proper size is based on tensioning of the supraspinous ligament and radiographic evaluation with appropriate compression or distraction (▶ Fig. 43.7). Placement of deep interspinous or interlaminar bone grafts should be done prior to final insertion of the device. Alternatively, interfacet or even intertransverse fusion with the use of local autograft, allograft, bone graft extenders, or iliac autograft may be performed via standard grafting techniques (▶ Fig. 43.8). In the event of a spinous process fracture, conversion to pedicle screw fixation can be done to achieve stability. Intraoperative lateral fluoroscopy confirms appropriate levels and device placement with standard follow-up care and radiographs (▶ Fig. 43.9). Multiple levels can be treated.

43.9 Difficulties Encountered

Wilson or Andrews frame or tables can induce kyphosis. Injury to the supraspinous ligament, facet joints, and wrong-level anatomy may occur without judicious care. SPP reconstruction is not a replacement for appropriate standard spinal decompression, including diskectomies and foraminotomies. Trimming of spinous processes (particularly when adjacent "kissing" occurs) is often needed. Oversizing can increase segmental kyphosis leading to failure and increased diskal pressures,

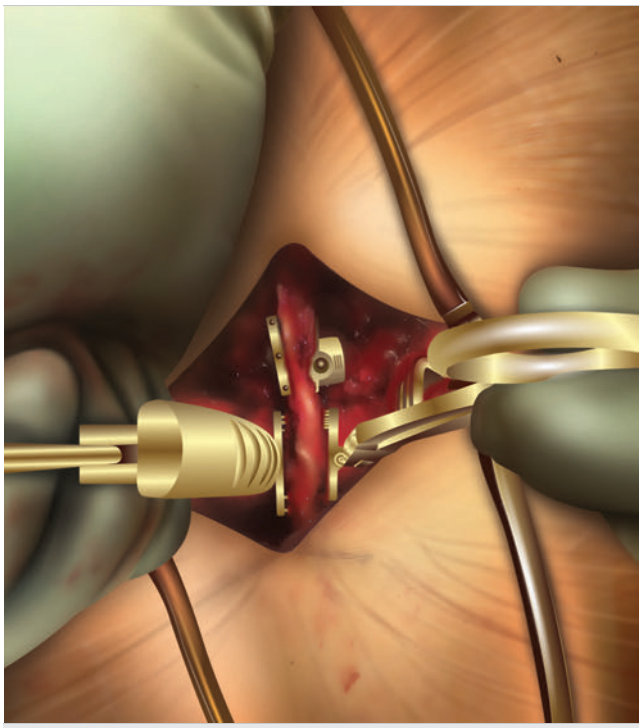

Fig. 43.6 Intraoperative photograph demonstrating placement of second plate.

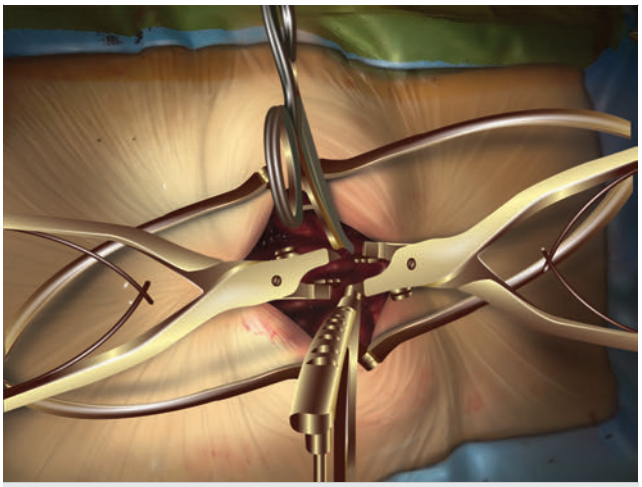

Fig. 43.7 Intraoperative photograph demonstrating plate compression.

which may increase disk degeneration. Placement of multiple devices is more demanding and can be associated with increased complications relating to spinous process fractures or malpositioning.

43.10 Key Procedural Steps

- Patient is placed in the prone position on radiolucent table (Jackson preferably to maintain segmental lordosis) after undergoing general anesthesia
- Fluoroscopic lateral localization is performed.
- Posterior midline approach is utilized and the paraspinal muscles are elevated off of the spinous processes at the desired level with preservation of the midline ligamentous structures.
- A decompression is performed as indicated.
- Interspinous awl placed (▶ Fig. 43.3).
- Interspinous distracter placed (▶ Fig. 43.4).
- Trialing device determines appropriate size.
- Correct size implant is obtained and is implanted securing to adjacent spinous processes (▶ Fig. 43.5, ▶ Fig. 43.6, ▶ Fig. 43.7)
- Additional level(s) placed in similar fashion as indicated.
- Decortication then interspinous, interlaminar, interfacet, or intertransverse arthrodesis performed with bone grafting (▶ Fig. 43.8).
- Final radiographic images are taken (▶ Fig. 43.9).

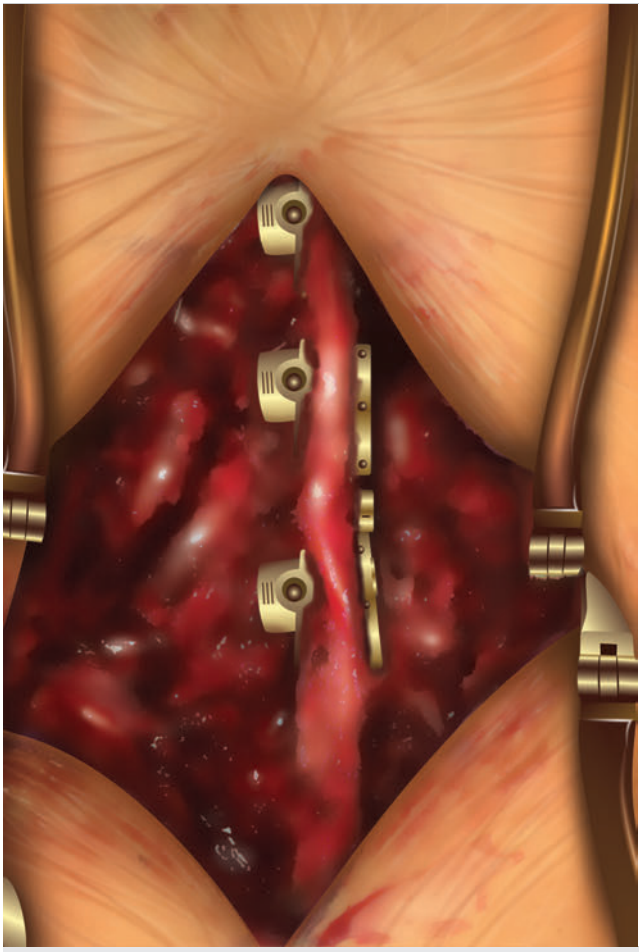

Fig. 43.8 Intraoperative photograph demonstrating final multilevel plating with bone grafting.

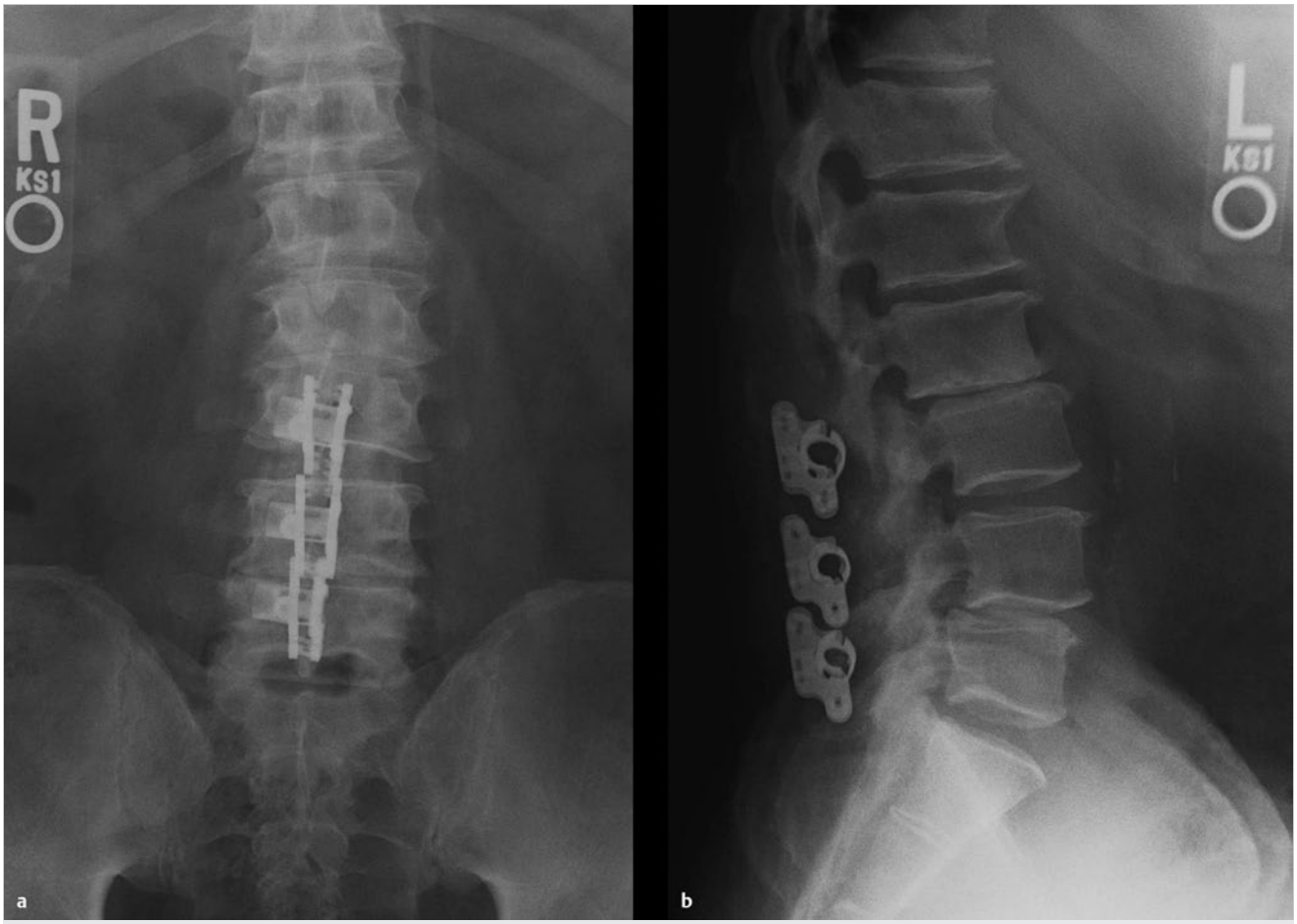

Fig. 43.9 Six-month postoperative (**a**) anteroposterior and **(b)** lateral radiographs demonstrating stable alignment.

43.11 Bailout, Rescue, and Salvage Procedures

In the event of a spinous process fracture or gross motion noted, conversion to pedicle screw fixation is often necessary to achieve stability. Postoperative bracing may be considered in patients with poor bone quality or fixation.

Pitfalls

- Performing spinous process plating in patients with significant osteoporosis may increase the potential for spinous process fractures.
- Oversizing the implant (interspinous process spacer) leads to both an increased risk of spinous process fracture and an increased risk of kyphotic alignment.
- The most critical portion of a lumbar spine case is the decompression; failure to achieve a complete decompression of the neural elements will lead to poor outcomes.

44 Transfacet Fixation

Christopher Chaput and Brian W. Su

44.1 Description

Transfacet screws (TFSs) traverse the lumbar facet to achieve biomechanical stability and arthrodesis.

44.2 Key Principles

Safe trajectories can be utilized for TFSs that decrease segmental motion and apply strong compression across the facets to aid bone healing.

44.3 Expectations

Transfacet screws can be inserted percutaneously or with a small midline incision, which can help limit postoperative pain, length of stay, and surgical site morbidity.

44.4 Indications

- Posterior lumbar fixation to augment interbody fusions
- Stabilize an interbody segment felt unstable following a decompression. This should be considered as a stand-alone option if the disk height of the instrumented segment is < 80% of normal.

44.5 Contraindications

- Pars fracture
- Significant deformity (significant spondylolisthesis, scoliosis, or kyphosis)
- Extensive resection of the pars or facet during decompression
- Lack of high-quality intraoperative fluoroscopy

44.6 Special Considerations

An understanding of the anatomical relationship of the facets and how they can be altered by degenerative changes is critical to performing this procedure safely and effectively. Because the screws are generally more cortical in nature and placed utilizing lag techniques, an understanding of the basic principles of cortical screw fixation is critical to achieving robust immobilization of the facet joints. The hard, subchondral bone of the facet is typically extremely dense, even in the older patient. Placing as many threads as possible across this bone will improve fixation more than placing a longer screw into the more cancellous bone found in the pedicle in the osteopenic patient.

44.7 Special Instructions, Positioning, and Anesthesia

Transfacet screws are most often placed with limited exposure with the use of fluoroscopy. Unlike pedicle screws, a 35-degree oblique "scotty dog" view is critical to ensuring safe screw placement (▶ Fig. 44.1). A Jackson table or similar radiolucent table makes visualization easier. The hips should not be placed in flexion at the time of instrumentation. This decreases lordosis and potentially distracts the facets, which need to be well opposed to pass a screw across them.

44.8 Tips, Pearls, and Lessons Learned

In the early part of the learning curve and when imaging is suboptimal, a small midline incision that enables direct visualization of the starting point can help the procedure progress smoothly and quickly. Any significant deformity or instability should be avoided with this technique, as in these situations the facets are usually deformed or malaligned. Transfacet screws are technically much easier to insert in the lower lumbar segments due to facet morphology. The sagittal facet orientation in the upper lumbar region makes facet screw placement more technically difficult. In anatomical studies, the L2–L3 segments could not be instrumented from the ipsilateral side due to its vertical facet orientation.

44.9 Difficulties Encountered

- The starting point can be difficult to achieve. Removing a small amount of the cephalad spinous process with a bur can help get the appropriate amount of medial to lateral angulation when the spinous process is bulbous and the interpedicular distance is narrow.
- Hypertrophic ("heaped up") facets can cover the normal starting point and make the tip of the trocar skive. A small midline incision, with exposure of the problematic starting point, allows the surgeon to remove any osteophytes in the way, and visually confirm the starting point. This also allows the dorsal aspect of the facet to be debrided and bone packed along the facet to encourage bone healing.

44.10 Key Procedural Steps

True anteroposterior (AP) and lateral fluoroscopic views should be obtained. The end plates of the levels to be fused should be clear and centered on the screen. The spinous process should be well centered between the two pedicles. The screw trajectory is "down and out." This typically requires a midline incision at the level of the cephalad spinous process. The skin incision varies with wound depth, the level instrumented, and normal anatomical variation. The incision can be mobilized both to the left and right to allow for placement of both TFSs through a single midline incision. If the procedure is done open, a standard subperiosteal dissection is performed and the facets are identified. The starting point is marked with a bur at the level of the inferior end plate of the cephalad vertebral body just medial to the medial border of the pedicle of the cephalad vertebra

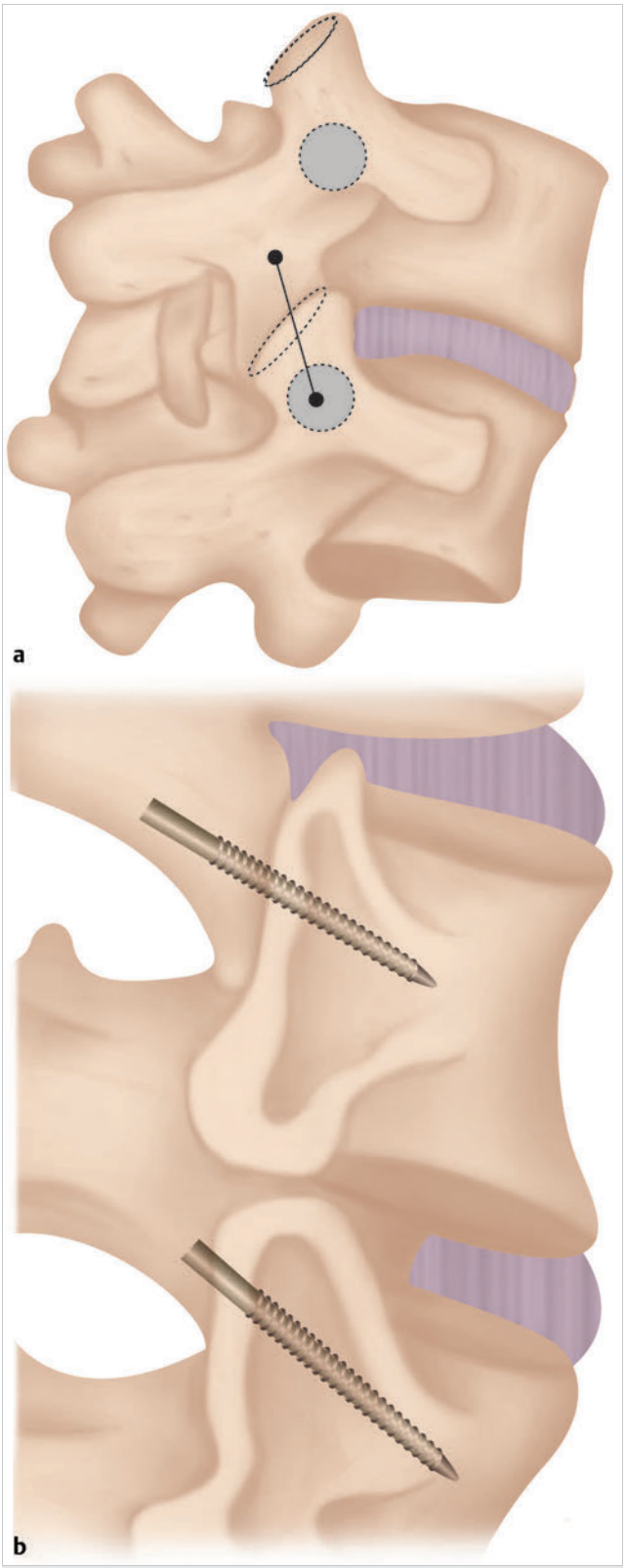

Fig. 44.1 A 35-degree oblique "scotty dog" view is critical to ensuring safe screw placement. This view ensures that the screw traverses through the center of the facet.

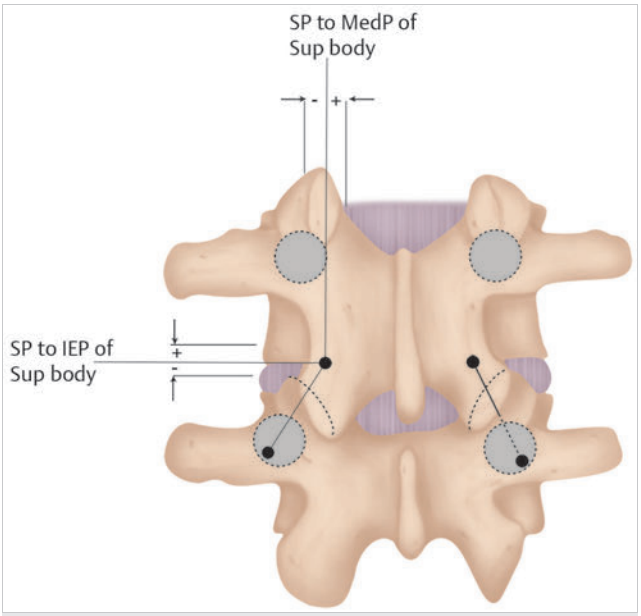

Fig. 44.2 The starting point is at the level of the inferior end plate of the cephalad vertebral body just medial to the medial border of the pedicle. This trajectory is designed to traverse the facet joint and terminate at the inferolateral quadrant of the caudal pedicle.

(▶ Fig. 44.2a, b). A disposable biopsy trocar (Jamshidi) or cannulated wire guide is then docked on the starting point. A lateral view is then taken to confirm the trocar is headed caudally in the direction of pedicle. Ideally, the tip of the TFS terminates in the inferolateral quadrant of the pedicle where it joins the vertebral body (▶ Fig. 44.2b). The washers on newer systems allow for small variations in the starting point; however, care should be taken to avoid placing the starting point caudal to the promontory of the facet on the lateral view to avoid skiving inferiorly and/or fracturing off the inferior facet of the cephalad vertebra.

Once the trocar/guide is in good position a threaded Kirschner (K-) wire is passed through the trocar and drilled through the two surfaces of the facet joint. Anteroposterior and lateral images are again taken to review the trajectory. A 30-degree oblique can be helpful at this point, as it will show the trajectory across the facet the most clearly (▶ Fig. 44.1). The K-wire is then advanced down (25–30 degrees caudal) and out (15 degrees lateral) until it contacts the lateral aspect of the pedicle vertebral body. This is viewed on the AP image. If the K-wire breaches the lateral or inferior pedicle on the AP image prior to passing the pedicle–vertebral body junction (on the lateral image), the K-wire has been advanced too far. On the lateral view, the screw should traverse the facet joint and terminate at the base of the pedicle where it meets the vertebral body (▶ Fig. 44.3).

A reamer is then passed over the K-wire and just across the two articular surfaces. These surfaces can be quite difficult to penetrate, and a loss of resistance is felt with the reamer as soon as it breaches the second cortex. Alternatively, a drill can be used without a K-wire with a more open technique.

The screw length is measured off of the K-wire. The typical screw length is 30 to 35 mm and width is 3.5 mm or 4.5 mm. The joint will compress a millimeter or two if a lag screw is

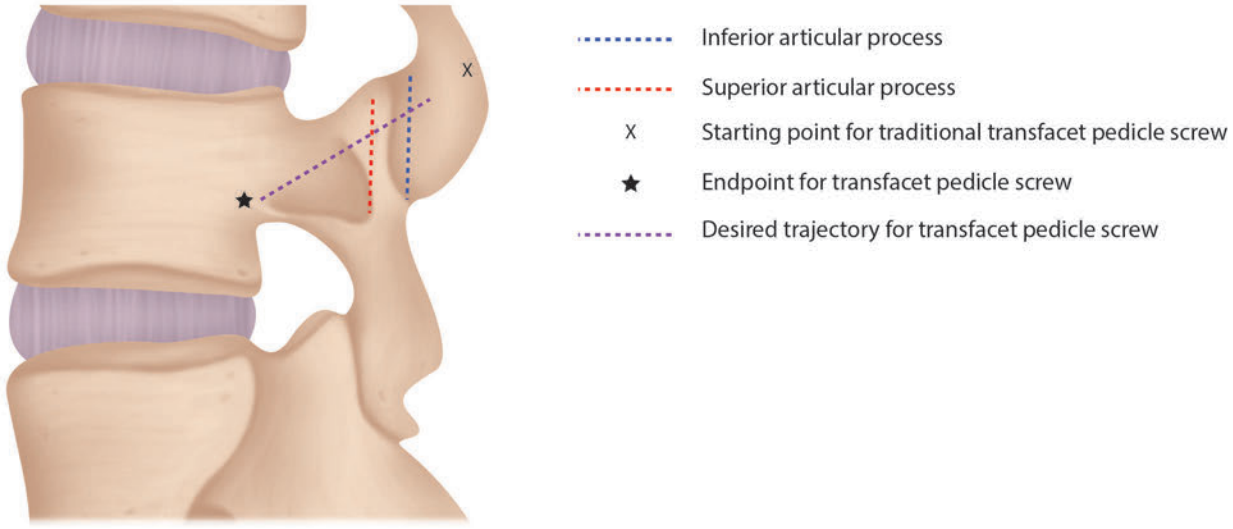

Fig. 44.3 On the lateral view, the screw should traverse the facet joint and terminate at the base of the pedicle where it meets the vertebral body.

used, and most screws will tend to strip if they hit the hard bone of the lateral pedicle, so it is important to take about 3 to 5 mm off of the measured length to prevent this.

44.11 Bailout, Rescue, and Salvage Procedures

- Misdirected K-wire: It can be difficult to redirect the K-wire, as it tends to follow the previous track. If the starting point can be moved slightly, a new trajectory can be created.
- Stripped lag screw: Usually, the tip of the screw has hit the lateral border of the pedicle or vertebral body. Use the next larger diameter screw, shortening the screw (usually by 5 mm), and use a fully threaded screw to get additional purchase from the subchondral bone of both sides of the joint. Some surgeons prefer to use fully threaded screws routinely for this reason.
- Poor bone quality compromising screw fixation: Use a larger diameter, fully threaded screw and take care to purchase as much cortical bone as possible.
- Fracture of the pars interarticularis, facet, or stripping of the largest diameter screw: Have a traditional pedicle screw system available. Traditional pedicle fixation after attempted TFS fixation is usually straightforward.

Pitfalls

- Poor fluoroscopic quality can prevent safe screw placement. The lower quality the fluoro, the more "open" the procedure should be to allow for direct inspection of starting points and trajectories. Laminotomies can be used that allow for both a decompression and direct palpation of the pedicle and lamina with a Woodson elevator to ensure correct placement.
- The starting point can be difficult to achieve. Removing a small amount of the cephalad spinous process with a bur can help get the appropriate amount of medial to lateral angulation when the spinous process is bulbous and the interpedicular distance is narrow.
- Hypertrophic ("heaped up") facets can cover the normal screw starting point and make the tip of the trocar skive. A small midline incision, with exposure of the problematic starting point, allows the surgeon to remove any osteophytes in the way, and visually confirm the starting point. This also allows the dorsal aspect of the facet to be debrided and bone packed along the facet to encourage bone healing.
- The K-wire should appear straight on the monitor. If it appears to bend or deflect significantly, it is likely that it has breached a cortex inadvertently and is bending as it reaches another cortex. Usually the K-wire is hitting the hard bone on the medial wall of the pedicle and skiving down it. The traversing nerve root can be irritated or injured at this point. If this is not realized, the reamer or K-wire can fracture the medial facet.
- The K-wire can come out with the reamer, especially if the reamer was passed distally past the facet joint. If this occurs, the K-wire can be replaced with a blunt K-wire and the position checked fluoroscopically.
- The K-wire can go beyond the lateral cortex of the pedicle and into the retroperitoneal space. Care should be taken to maintain control of the proximal portion of the K-wire with a Kocher clamp.

45 Intrailiac Screw/Bolt Fixation, S2 Alar Iliac Screw Fixation

Ryan P. Ponton, Nelson S. Saldua, and James S. Harrop

45.1 Description

Intrailiac screw/bolt and S2 alar iliac (S2AI) screw fixation constructs utilize a pelvic anchor to fixate the lumbosacral spine to the pelvis for stability and deformity correction. With long fusions to the sacrum, it is critical to protect sacral screws with iliac fixation. Whether it is better to use iliac fixation or S2AI fixation is not clear.

45.2 Key Principles

Intrailiac and S2AI screw fixation provides a biomechanical advantage over sacral instrumentation through secure anchors in the pelvis. The screws cross anterior to the sagittal vertical axis, or sagittal plumb line without compromising sacroiliac joint stability. Multiple studies have shown a high pseudarthrosis rate and poor outcome associated with fixation failure when S1 promontory screws are used without supplemental fixation.

45.3 Expectations

Distal fixation in spinal deformity surgery is critical when arthrodesis to the sacrum is indicated. Intrailiac fixation and S2AI screw fixation provide a solid distal foundation, in addition to protecting S1 screws.

45.4 Indications

- Long or multisegmental fusions extending to the pelvis (e.g., scoliosis, trauma, low lumbar osteotomy)
- Neuromuscular scoliosis correction with pelvic obliquity
- Reconstruction procedures after sacrectomies
- Fixation for unstable sacral fractures
- Adjunct posterior stabilization method for high-grade lumbar spondylolisthesis
- Salvage procedures for revision lumbosacral operations

45.5 Contraindications

- Active spinal infection
- Pelvis insufficiency (i.e., extensive previous iliac crest bone graft harvesting)

45.6 Special Considerations

Plain radiographs of the thoracolumbar spine, including standing long cassette views (36-inch), will allow for evaluation of coronal and sagittal balance. Additionally, plain radiographs of the pelvis as well as dynamic lateral flexion and extension images of the lumbar spine are recommended. In revision cases, particularly ones where there was prior posterior iliac crest bone graft harvest, a computed tomography (CT) scan of the pelvis provides further information for preoperative planning.

45.7 Special Instructions, Positioning, and Anesthesia

- Patients are placed in the prone position on a Jackson-type frame, taking care to prevent excessive pressure on bony prominences and the orbits.
- Operating table should maintain desired sagittal alignment with physiologic lumbar lordosis (e.g., four-post bed, Jackson table).
- A radiolucent operating table allows for the use of intraoperative fluoroscopy.

45.8 Tips, Pearls, and Lessons Learned

Placement of the iliac or S2AI screw from the contralateral side of the table provides for a more optimal sense of screw trajectory. An osteotomy or harvesting bone from the posterior iliac crest can result in weakening at the insertion site. Therefore, bone graft harvesting should be planned after iliac screw placement.

Intraoperative fluoroscopy or plain radiographs can evaluate the final position of screw placement:

- Sciatic notch: Obturator oblique view
- Hip joint: Pelvic inlet and outlet views
- Medial wall: Iliac oblique view
- Lateral wall: Difficult to detect by plain radiographs/fluoroscopy
- Screw length is typically less than 90 mm for both iliac and S2AI techniques. A greater length may penetrate into the hip joint. Screw diameter:
  - Males: 8-mm implants
  - Females: 6- to 7-mm implants

Placement of S1 screws should be done prior to iliac or S2AI screw placement. This provides for an accurate assessment of screw-to-screw distance and positioning to facilitate construct assembly.

45.9 Difficulties Encountered

- Breach of the cortical surfaces with the screw placement. With S2AI screws, posterior penetration is more likely than anterior penetration.
- Medial cortical wall penetration may result in injury to intrapelvis neurovascular structures, specifically the lumbosacral plexus.
- Violation of the sacral notch may result in the following:
  - Injury to the sciatic nerve
  - Injury to superior gluteal artery with subsequent retroperitoneal hematoma formation and blood loss
- Prominence of hardware with pressure ulceration formation and subsequent infection

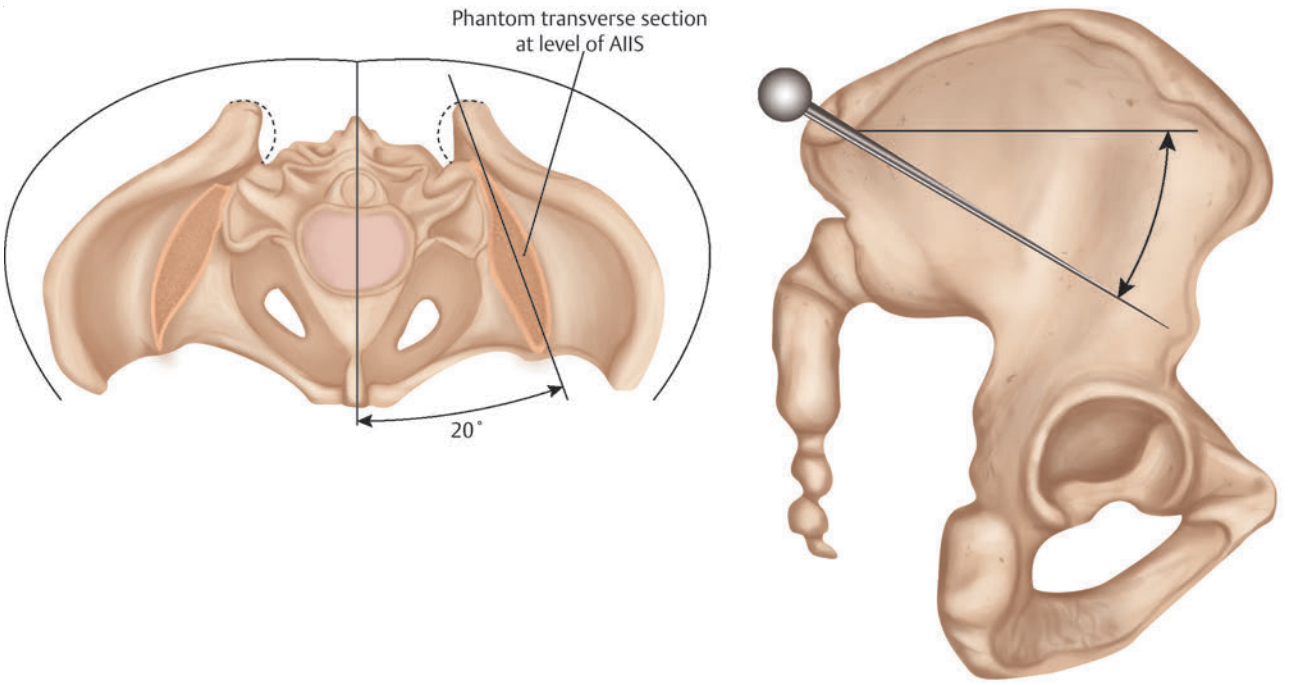

Fig. 45.1 Trajectories for intrailiac screw placement. (**a**) Transverse plane. General trajectory is 20 degrees lateral to the midsagittal plane. (**b**) Sagittal plane. General trajectory is 30 to 35 degrees caudal to the transverse plane, directed towards AIIS. AIIS, anterior inferior iliac spine.

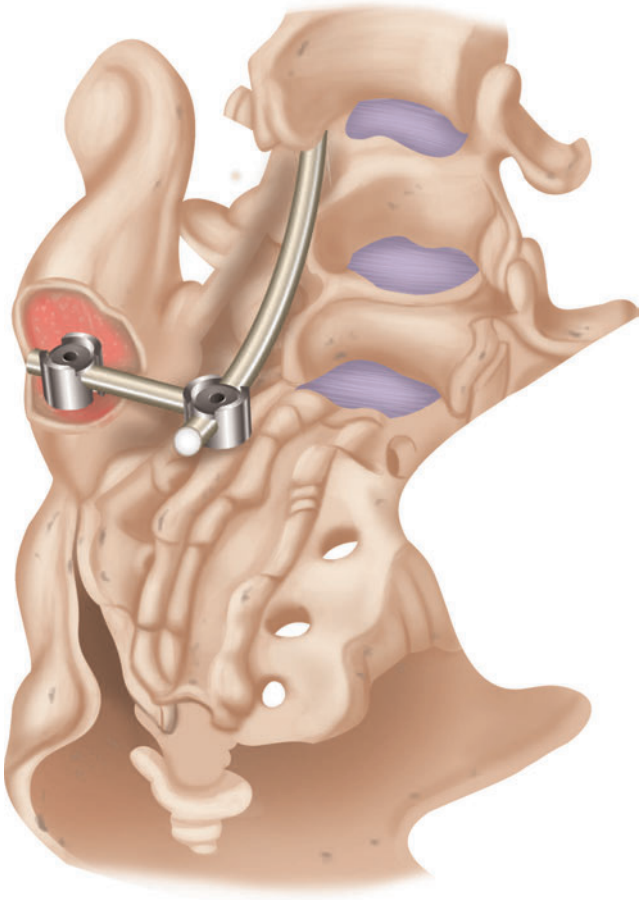

Fig. 45.2 Traditional iliac screw placement. Note the removal of the posterior iliac spine, which makes for a more lateral connection to the lumbosacral fixation construct.

45.10 Key Procedural Steps

45.10.1 Intrailiac Screw Placement

Surgical exposure is performed with a posterior midline incision down to the spinous processes of the lumbosacral junction. The posterosuperior iliac crest can be palpated and the erector spinae muscles are dissected from the midline in a medial-to-lateral direction in a subperiosteal manner to the medial border of the iliac crest, taking care not to disrupt its distal insertion to maintain muscle viability and prevent the formation of a dead space. The soft tissues (gluteal muscle attachments) on the lateral iliac crest wall are dissected off the ilium in a subperiosteal manner to allow finger palpation of the sciatic notch. The starting point for iliac screw placement is often the distal prominence of the posterosuperior iliac crest, which is anatomically located directly lateral to the S2 pedicle (▶ Fig. 45.1, ▶ Fig. 45.2). Precise screw starting point, however, is guided by the location of the sciatic notch, which is felt during screw path development.

A modification of this method of screw insertion, as developed by Vaccaro, begins the screw starting point along the medial border of the posterior iliac crest using a 5-mm bur to expose the intrailiac cancellous bone (▶ Fig. 45.3). This allows the polyaxial screw head of the iliac bolt to project medially over the sacrum, which eliminates the need for a lateral connector rod to mate the longitudinal component (spinal rod) with the iliac screw. This results in less hardware prominence. Once the starting point is chosen and developed, a blunt joystick is used to develop a screw path in a general trajectory of 20 degrees lateral to midsagittal plane and 30 to 35 degrees caudal to the transverse plane toward the anterior inferior iliac spine (▶ Fig. 45.1). Actual screw insertion trajectory is guided

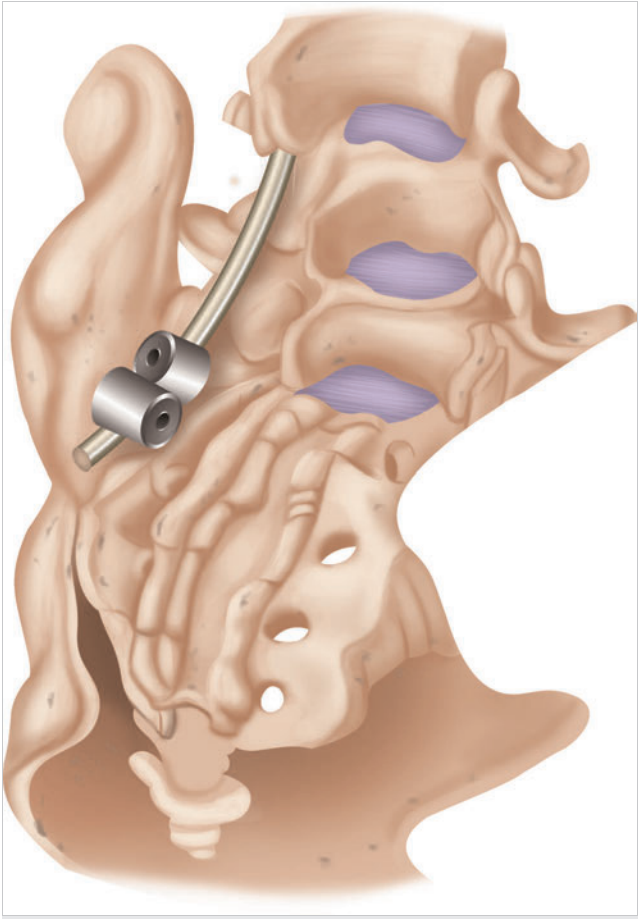

Fig. 45.3 Modification of intrailiac screw placement. The utilization of a starting point that is more medial provides for a straight connection to rest of the fixation construct, making construct assembly easier and decreasing hardware prominence.

through tactile finger palpation of the sciatic notch with the goal of screw passage within 1.5 to 2 cm above the sciatic notch. The sciatic notch is made of thick cortical bone above which a narrow isthmus exists for screw passage. Therefore, if resistance is met to probe or screw placement, then the trajectory must be modified. The intended screw path is confirmed with a ball tip probe to detect any cortical breaches. The iliac screw is then inserted. The head of the polyaxial screw is assessed in relationship to the surrounding posterior iliac crest bone and soft tissues to make sure it is not prominent. Fluoroscopy can be utilized to further assess and adjust screw placement.

45.10.2 S2 Alar Iliac Screw

The approach for S2AI screws is similar to the approach used for intrailiac screw fixation. Like intrailiac screws, the placement of S2AI screws should only take place after the other points of fixation have been secured.

Using standard anteroposterior (AP) pelvis and inlet fluoroscopic views, the S1 dorsal sacral foramen is identified. The starting point is in line with the lateral edge of the S1 foramen and 5 to 10 mm distal to the S1 foramen (▶ Fig. 45.4). An awl is used to breach the cortex for the starting point. The S2AI trajectory averages 40 degrees of lateral angulation in the transverse plane and 40 degrees of caudal angulation in the sagittal plane, aiming towards the anterior inferior iliac spine (AIIS).

An extended length 2.5-mm drill bit is used to tap through the sacral ala, SI joint, and ilium. This distance is approximately 30 to 45 mm. An extended length 4.2-mm drill bit is used to drill to a depth of approximately 80 to 90 mm. A ball-point depth gauge is used to determine the length of the screw. A 1.45-mm guidewire mounted on a handheld driver is advanced for an additional 10 to 20 mm to seat the guidewire in bone.

Confirm placement with fluoroscopy. The hole is manually tapped over the guidewire. The screw of appropriate length is placed.

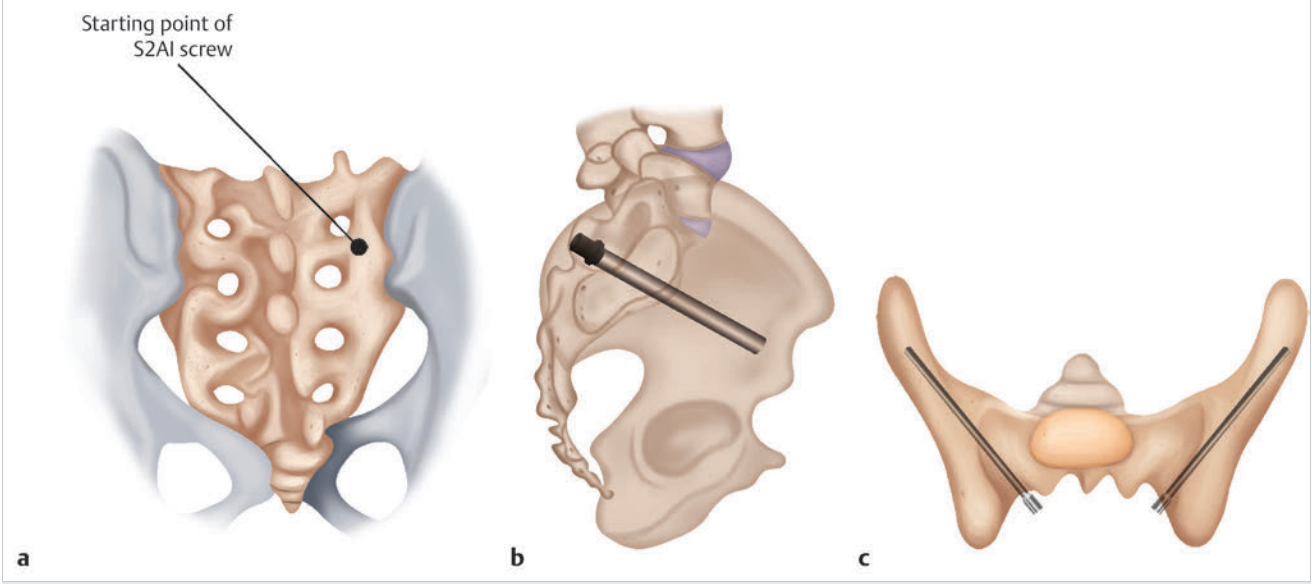

Fig. 45.4 **(a)** S2 alar iliac (S2AI) screw starting point: Lateral edge of S1 foramen and 5 to 10 mm distal to the S1 foramen. (**b**) Sagittal trajectory averages 40 degrees of caudal angulation, aiming towards the anterior inferior iliac spine (AIIS). (**c**) Transverse plane screw trajectory averages 40 degrees of lateral angulation.

45.11 Bailout, Rescue, and Salvage Procedures

A cortical breach can be detected by a change in the joystick or pelvic probe resistance. This defect can be confirmed with a ball tip probe or sound. The defects are typically in the lateral wall prior to entering the sciatic notch. If the sciatic notch was not initially palpated, then subsequent dissection and palpation will further define the correct screw trajectory. The utilization of fluoroscopy may be of further assistance.

Inability to pass the probe can occur when contacting the thick cortical margins around the sciatic notch. Reconfirming and modifying the trajectory of the approach typically resolve this issue. Again, fluoroscopy may be of further assistance.

Passage of the probe into the hip joint is detected with a void at the distal end of the hollowed intended screw path. This typically does not occur with placement of an iliac screw shorter than 80 cm in men and 60 cm in children or women. Fluoroscopy with pelvic inlet and outlet views demonstrates this region and can confirm screw location in relation to the hip joint.

Pitfalls

- Violation of the cortical boundaries
- Inability to advance probe
- Placement of screws into the hip joint

46 Iliosacral Screw Fixation and Transiliac Rod Placement Techniques

Anuj Singla and Adam Shimer

46.1 Description

Percutaneous iliosacral screw fixation and transiliac rod placement are methods designed to stabilize the iliosacral articulation. The method of percutaneous placement of screws across the sacroiliac joint provides excellent mechanical stability. Pelvic fixation using iliosacral screws can help stabilize the unstable pelvic fractures. It can also help stabilize long instrumentation constructs in deformity correction or degenerative spinal procedures. The use of a transiliac bar is to restore the mechanical continuity of the posterior osseoligamentous complex of pelvis.

46.2 Key Principles

This method of percutaneous screw instrumentation across the sacroiliac joint helps to restore the mechanical integrity of the pelvis. It requires anatomical closed or percutaneous reduction of the pelvis before the screw placement. Transiliac or sacral bar fixation is a well-recognized technique for the treatment of posteriorly unstable pelvic injuries, particularly sacral fractures. The transiliac sacral bars are placed in the iliac crest posterior to the sacrum. Restoration of pelvic stability and early mobilization has proven benefits with regards to reducing mortality and morbidity in unstable pelvic fractures. Tile type C vertical shear pelvic disruptions are best treated surgically by fixation of the unstable posterior pelvic complex. It can also be used as an alternate form of pelvic fixation (distal anchor of complex spinal instrumentation) in cases of difficult sacral or pelvic screw fixation.

46.3 Expectations

Percutaneous placement of these can provide a strong fixation in the pelvis without too much soft tissue dissection or blood loss. The minimal tissue dissection and stability provided allows in some instances for immediate/early weight bearing.

Cadaveric studies have shown that iliosacral screw and sacral bars provide acceptable stability in cases of vertically unstable fracture without the need of anterior pelvic fixation. The screws and bars provide 70 to 85% resistance to axial and torsional loading. By combining SI screws with transiliac bars, approximately 90% of intact pelvic stability can be achieved.

46.4 Indications

Iliosacral screws provide an excellent fixation option in carefully selected patients. It is most commonly utilized as a standalone form of instrumentation or in combination with anterior pelvic fixation for vertically unstable pelvic fractures, U-shaped sacral fractures, and Dennis-type I and II sacra fractures. Other indications include augmenting pelvic fixation in cases of complex spinal deformity correction and spondylopelvic dissociation and fusion across painful and degenerative sacroiliac joints.

46.5 Contraindications

This technique relies heavily on the ability to visualize the anatomical landmarks for screw entry point and screw trajectory. Therefore, this technique is relatively contraindicated in patients with pelvic dysmorphism or where the patient's injuries or habitus preclude the use of fluoroscopy. The recent advances in imaging techniques like 3D fluoroscopy, computer navigation-assisted surgeries, and intraoperative computed tomography (CT) scans can help to better define the anatomy and hence screw placement.

Comminuted sacral fractures are also a contraindication for this procedure as the screws can cause overcompression and neural entrapment especially with bony involvement of the sacral neuroforamina. Fixation with transiliac sacral bars requires that one hemipelvis be intact posteriorly for anchorage of the opposite unstable pelvis.

46.6 Special Considerations

Due to anatomical variations of the sacroiliac joint, the proximity of the fifth lumbar nerve root, and iliac vessels close to the screw trajectory, preoperative CT scanning and intraoperative fluoroscopic guidance are essential in placing the screw accurately. CT imaging helps in defining the exact fracture pattern.

46.7 Special Instructions, Positioning, and Anesthesia

Although the procedure can be done in the supine, prone, or lateral position, the supine position is generally recommended as it allows for simultaneous assistance in postural fracture reduction. It is also the most favored position in polytraumatized patients. The patient is placed in a supine position on a radiolucent table with a sterile draped leg that will allow for intraoperative manipulation for indirect fracture reduction maneuvers.

46.8 Tips, Pearls, and Lessons Learned

Urinary catheters are recommended for reduction of bladder volume and when possible also a bowel enema for an unobstructed visualization of the bony pelvis during fluoroscopic imaging. Neuromonitoring is advocated during screw placement. The lateral ilium starting point is at the junction of the posterior sacral body in the sagittal plane and at the inferior S1

foramen in the coronal plane. S2 iliosacral screws are reported to have less cross-sectional area for placement than S1 screws. The positioning of the lower screw in the second sacral vertebral body is reported to be associated with a higher change in neurologic impairment; therefore, it is avoided if possible. However, if necessary, the safety window of a S2 screw can be increased by placing it closer to the S1 foramen within the S2 vertebral body. With regard to transiliac sacral bar placement, a cadaveric study found that the entire length of the posterior iliac crest from the level of the upper border of the L5 lamina to the posterosuperior iliac spine was safe and adequate for transiliac sacral bar placement with the best bony purchase at the level of the L5–S1 joint. This was the safest location of insertion and offered the best bony purchase. There is an increased risk of violating the sacral canal below this level. Overtightening the sacral nuts must be avoided, especially in the treatment of vertical transforaminal sacral fractures, to prevent compression of the sacral nerves.

46.9 Key Procedural Steps

External fixators or Schanz screws can be used as reduction aids (joysticks). Pelvic lateral, inlet, and outlet view should be checked after positioning by rotating and steering the fluoroscope. The inlet view shows the relationships of the spinal canal and the sacroiliac joint; the outlet view demonstrates the upper border of the sacrum and the sacral foramina and the lateral view illustrates the anterior border of the sacrum.

A lateral stab incision is used for screw insertion. Cannulated partially threaded screws (diameter: 6.5–8.0 mm) can be used as lag screws. The screws are placed over a 3.2-mm guidewire. A guidewire is inserted percutaneously through the gluteal region down to the outer table of the ilium. Using radiographic control, the guidewire is drilled across the ilium and into the first or second sacral segments. Insertion depth is determined by fracture configuration. Sacroiliac dislocations may require that the screw only enters the sacral ala, whereas sacral fractures may require screws into the sacral bodies.

For transiliac sacral rod fixation the patient is positioned in the prone position. The rod insertion site is approximately 2 cm anterior to the posterior superior iliac spine. The rod is driven through the ilium toward the opposite side. The rod is positioned posterior to the sacrum, which is confirmed using the lateral fluoro imaging. The rod is cut to the appropriate length after confirmation of correct placement. The rod is then secured using washers and nuts on the outer aspect of the ilium. The rod can be used a stand-alone fixation device for sacral fractures or it can be connected to cephalad spinal instrumentation.

46.10 Difficulties Encountered

Malposition of the screw is common and its rate varies depending on the type of imaging used and the surgeon's experience (3–20%).

L5 nerve root and internal iliac vessels are at risk in cases of screw malposition and perforation. Small bowel obstruction from entrapment in a sacral fracture and ureteral injuries have been reported with these screws.

46.11 Bailout, Rescue, and Salvage Procedures

The surgeon may use as a bailout an external fixator or process with an open reduction and internal fixation of the pelvis.

Pitfalls

- The method of screw placement relies to a great extent on the ability to visualize the anatomical landmarks, which involves significant exposure to radiation for the surgical team and the patient.

47 Intrasacral (Jackson) and Galveston Rod Contouring and Placement Techniques

Roger P. Jackson and Douglas C. Burton

47.1 Description

The intrasacral (Jackson) screw and rod fixation technique involves the safe insertion of intrasacral screws and rods into the best bone possible with avoidance of injuring the surrounding neurovascular structures. The Galveston technique of intrailiac anchorage utilizes careful osseous placement of a three-dimensionally contoured rod, taking into account spinopelvic deformity and allowing for connection to other lumbosacral anchors.

47.2 Key Principles

47.2.1 Intrasacral (Jackson) Technique

Insertion of the S1 screw head into the lateral sacral mass where the head is much closer to the back of the L5–S1 disk, as well as the L5 and S1 vertebral bodies, significantly reduces bending loads on the screw/rod construct at the L5–S1 level and increases the stiffness of the fixation. The low- to no-profile rod/screw construct provides an interlocked, "sacroiliac buttress" type of fixation that allows for application of in situ rod contouring principles to create lumbopelvic lordosis and better balance.

47.2.2 Galveston Technique

Intrailiac anchorage provides a strong sacropelvic foundation for long spinal constructs crossing the lumbosacral junction while maintaining a low profile in a patient population where implant prominence is often a significant concern.

47.3 Expectations

47.3.1 Intrasacral (Jackson) Technique

- Increased sacropelvic fixation in three planes without bridging the sacroiliac (SI) joints or compromising the iliac crests
- Posterior lumbosacral instrumentation that provides for improved biomechanics and increased lordosis in the distal lumbar spine with essentially no profile on the back of the sacrum

47.3.2 Galveston Technique

The bilateral placement of carefully contoured rods in the supra-acetabular intrailiac passageway provides a strong sacropelvic foundation for the correction of rigid spinopelvic deformity and resists the flexion–extension and rotation forces that exist. This strong and stable foundation facilitates the establishment of a solid arthrodesis across the lumbosacral junction in long spinal constructs.

47.4 Indications

- Long spinal deformity fusions to the sacrum
- Spondylolisthesis
- L5 burst fractures
- Lumbar flatback
- Osteopenia or osteoporosis
- Revisions including L5–S1 pseudarthrosis

47.5 Contraindications

47.5.1 Intrasacral (Jackson) Technique

- Congenital abnormalities
- Tumors
- Infections involving the proximal sacrum

47.5.2 Galveston Technique

- Abnormalities of iliac anatomy that preclude the placement of anchorage
- Severe osteopenia

47.6 Special Considerations

A computed tomography (CT) scan to better delineate the sacral anatomy should be taken preoperatively. A CT also is helpful in the setting of a previous or planned pelvic osteotomy, or prior bone graft harvest that has altered the normal iliac orientation for the Galveston technique.

47.7 Special Instructions, Positioning, and Anesthesia

The patient should be placed in a prone position on a surgical table or frame that provides for improved pulmonary compliance, reduced blood loss, unrestricted fluoroscopic imaging, and that preserves or creates increased lumbopelvic lordosis, such as the Jackson surgery table. Severe hip flexion contractures and lumbar hyperlordosis are critical to recognize and account for in patient positioning. If using a standard four-poster frame, the posts must be built up to allow for the hip flexion contractures and keep undue pressure off of the knees. Hyperlordosis should be recognized preoperatively and anterior releases performed, if needed. Positioning out of a hyperlordotic position can be aided with the use of two additional posts placed between the usual two. This eliminates, as much as possible, the sag that occurs between the posts, which accentuates lordosis.

In cases of severe fixed pelvic deformity, a single femoral traction pin placed on the "high pelvis" side with 20 pounds of traction (depending on patient size) can aid in the reduction of spinopelvic deformity.

47.8 Tips, Pearls, and Lessons Learned

47.8.1 Intrasacral (Jackson) Technique

Intraoperative anteroposterior (AP), lateral, and angled fluoroscopic images, by tilting of the C-arm in the sagittal plane to get a tangential view of the S1 endplate, are critical. Good AP fluoroscopic imaging of the sacrum is necessary for insertion of the intrasacral rods after the S1 screws have been deeply buried in the bone. The end of the rods should perforate the anterolateral cortex of the sacrum and not extend more than 5 to 10 mm beyond the distal aspect of the inferior SI joint.

47.8.2 Galveston Technique

Careful preoperative planning of types and locations of anchors, particularly if S1 pedicle screws are going to be used, is paramount. If S1 screws are planned, they should be placed prior to exposure of the iliac anchor, as this will help to show how far distally the iliac anchor must be placed. If using a pedicle bolt/connector system, short post screws are recommended, and often an open slotted connector is necessary, although not always. Transverse connection is important, and preferably performed between the S1 screws and iliac post, although anatomical considerations preclude this at times. Utilization of three- and four-rod constructs, depending on sagittal profile and coronal curve position, may facilitate Galveston rod placement. The use of a short Galveston rod on the concavity of the curve (high pelvis side) allows for ease of placement and the ability to distract against the longer, more proximally placed rod. This connection may make an S1 screw on the ipsilateral side unworkable due to bunching of connectors.

47.9 Difficulties Encountered

47.9.1 Intrasacral (Jackson) Technique

A transitional lumbosacral vertebra is not a contraindication, but may make insertion of the implants more difficult, especially with partial sacralization of L5. Closely spaced iliac crests can also make the procedure more difficult.

47.9.2 Galveston Technique

The neuromuscular patient population will frequently have severe, fixed pelvic obliquity in all three planes that makes contouring a challenge. The use of multiple rods improves, but does not eliminate, this problem. Myelomeningocele, due to its dysraphic posterior elements, widens the rod position, thereby making the connection to S1 screws and rod contouring more difficult.

47.10 Key Procedural Steps

47.10.1 Intrasacral (Jackson) Technique

A good intraoperative Ferguson view of the proximal sacrum with the C-arm is needed (▶ Fig. 47.1). A reduced-volume closed S1 screw head is deeply countersunk into the lateral sacral mass (▶ Fig. 47.2). A special angled sacral curette is then inserted through the screw head and used to open up and sound the lateral sacral mass (▶ Fig. 47.3). The length of intrasacral rod required can then be determined. A rod is cut to length, contoured, and directed distally into and through the closed canal of the S1 screw. Under fluoroscopic control, the rod is then worked caudally into the lateral sacral mass. The distal end of the rod is directed toward the inferior SI joint. The rod must be contoured properly and guided out laterally to get better fixation in the distal sacral mass adjacent to the SI joint. Rolling the curved rod to direct its distal end more laterally and anteriorly in the sacrum is helpful. The safest and strongest area is in the distal lateral sacrum adjacent to the SI joint. At no time is the rod intentionally driven across the sacroiliac joint. The pelvic anatomy in this area can provide considerable fixation and support for the end of the rod. This is especially so for resisting flexural bending moments. After the distal end of the rod has been driven caudally into the lateral sacral mass and out through the cortex, the proximal end is manipulated down and up into the other screw(s), then the set screw is tightened down in the S1 screw head. The second rod is implanted in the same way. ▶ Fig. 47.4 shows a typical multilevel construct with insertion of the intrasacral rods. The rod is positioned as closely to the back of the L5–S1 disk space as possible.

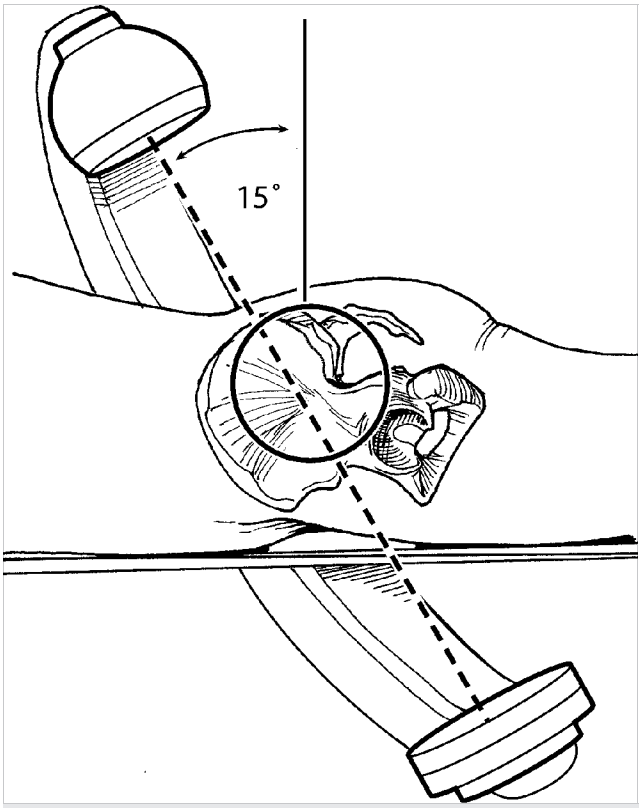

Fig. 47.1 Ferguson view with C-arm.

47.10.2 Galveston Technique

The successful placement of Galveston rods requires two equally important steps: establishment of the iliac passageway,

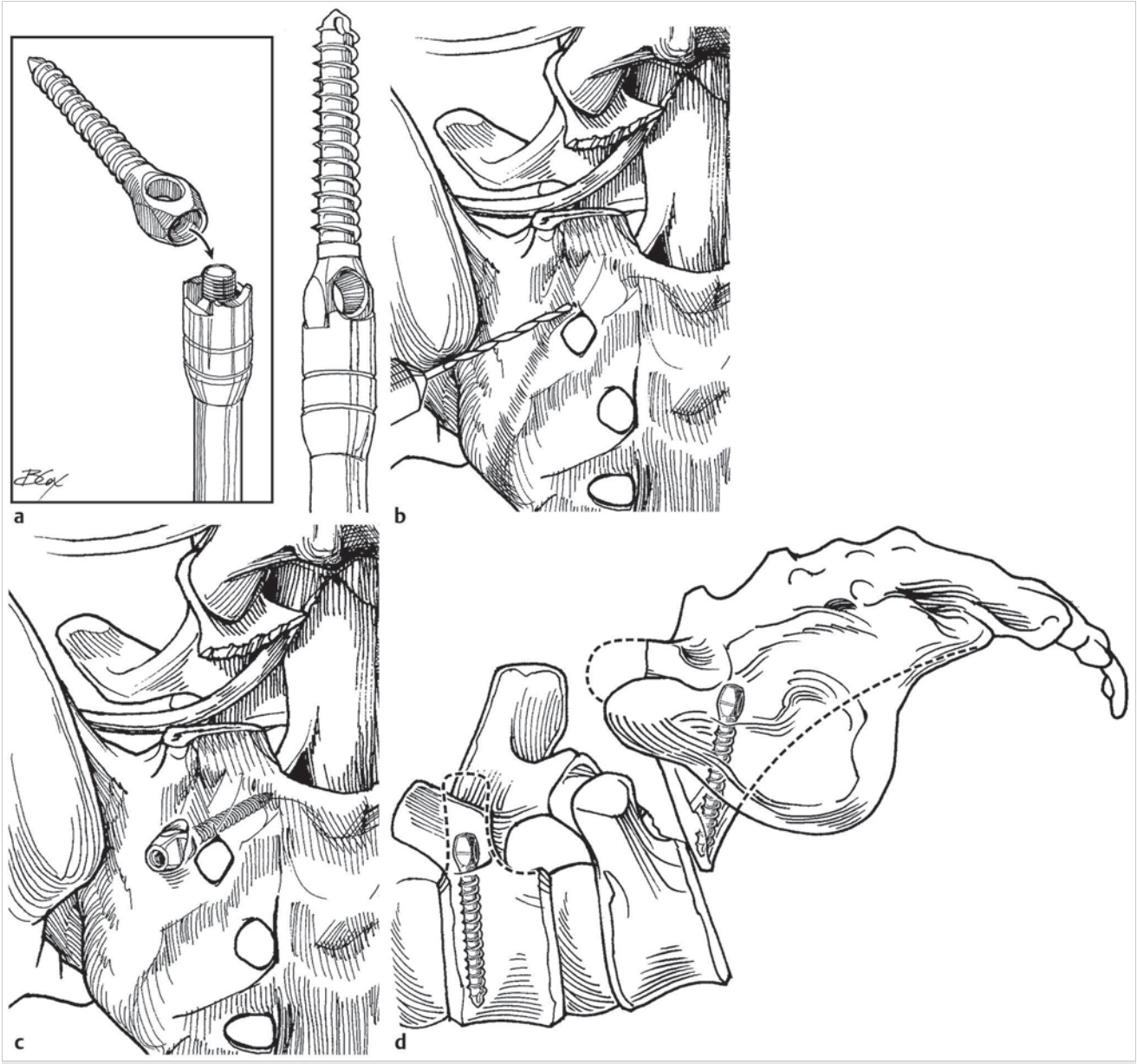

Fig. 47.2 **(a)** A reduced-volume closed screw. **(b)** The hole is started as far as possible laterally on the sacrum, with the iliac crest being the limiting factor. The drill bit is angled medially 10 to 15 degrees toward the anterior sacral promontory. **(c, d)** The reduced-volume closed screw is inserted.

and bending and insertion of the rod. The ilium is approached through a separate fascial incision made along the posterior-superior iliac spine (PSIS). The outer table is exposed in a subperiosteal manner and the sciatic notch is identified and marked with placement of an elongated Freer elevator (Slim Jim; Sklar Instrument Corp.) into the cephalad portion of the notch. This provides constant visual feedback to the surgeon (who stands on the opposite side of the table) during probing of the passageway. The very distal portion of the PSIS is removed with a rongeur down to the level of the sacrum. This improves the profile by keeping the host bone more dorsal than the implant and places the rod directly on the sacrum, also improving profile.

A standard blunt pedicle finder is used to probe the ilium. The starting point should be just medial to the lateral cortex, with the curved tip of the pedicle finder directed medially. Drilling is not recommended, particularly in osteopenic bone, as it increases the likelihood of a cortical breach. The orientation should be to a point 1.0 to 1.5 cm above the notch and along the lateral cortex. A medial starting point or directing the probe too proximally will potentially shorten the passageway. Most adults can accommodate 8 to 10 cm of a ¼-inch rod, whereas children have between 6 and 8 cm of length and thus accommodate ¼- or $^{3}/_{16}$-inch-diameter rods. A fine ball-tipped probe is used to search for any breaches of the cortical bone. The passageway is then widened with a dilator prior to final rod placement, as this decreases the chance of cutout during insertion.

Proper bending of a Galveston post requires four measurements and is facilitated by the use of variable radius benders

(two flat and two tube benders). The measurements required are (1) the length of the intrailiac segment (▶ Fig. 47.5a), (2) the transverse plane angle of the iliac fixation site to the midsagittal plane (▶ Fig. 47.5b), (3) the mediolateral distance from the iliac entry site to the intended line of longitudinal passage along the spine (▶ Fig. 47.5c), and (4) the length of rod from the sacrum to the most cephalad level of instrumentation (▶ Fig. 47.5d).

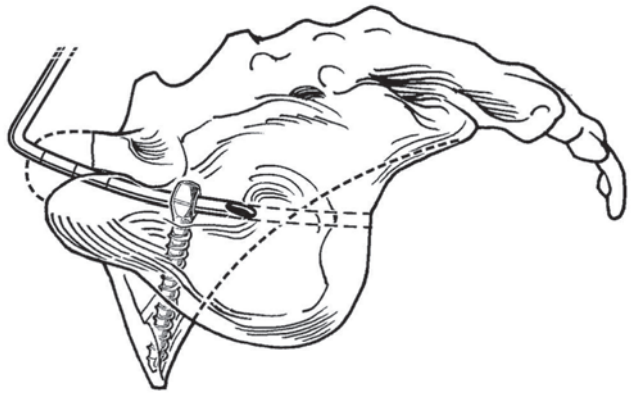

Fig. 47.3 A special angled sacral curette is inserted through the screw head and used to open up and sound the lateral sacral mass.

The initial bend is a right-angle bend using the tube benders. The short length is the sum of measurements 1 and 3 (the length of the intrailiac segment and the mediolateral distance from the iliac entry site to the intended line of longitudinal passage along the spine) and represents the sacroiliac portion of the rod. The next bend separates the short end of the rod into its iliac and sacral portions. The bend point is measured from the midportion of the right-angle bend and equal to measurement 3 (the mediolateral distance from the iliac entry site to the intended line of longitudinal passage along the spine) minus 3.0 mm (to account for the length of the bend). The plane of this bend is perpendicular to the plane of the right-angle bend and equal to measurement 2 (the transverse plane angle of the iliac fixation site to the midsagittal plane). The right-left orientation must be accounted for, and this bend is made with the tube bender on the iliac portion and the flat bender on the sacral portion of the rod. The sagittal plane contour is then achieved with the flat benders. It is important to allow for the length of the sacrum before beginning lordotic bending and to remember that L4–S1 lordosis is much greater (usually) than L1–L4. The final sagittal plane orientation of the iliac segment can be adjusted, if needed, with the flat benders, but is often not necessary.

The iliac rod segment is tunneled under the multifidus and inserted into the ilium with the spinal segment of the rod directed away from the back. The rod is then rotated toward the spine and the iliac segment impacted into the ilium.

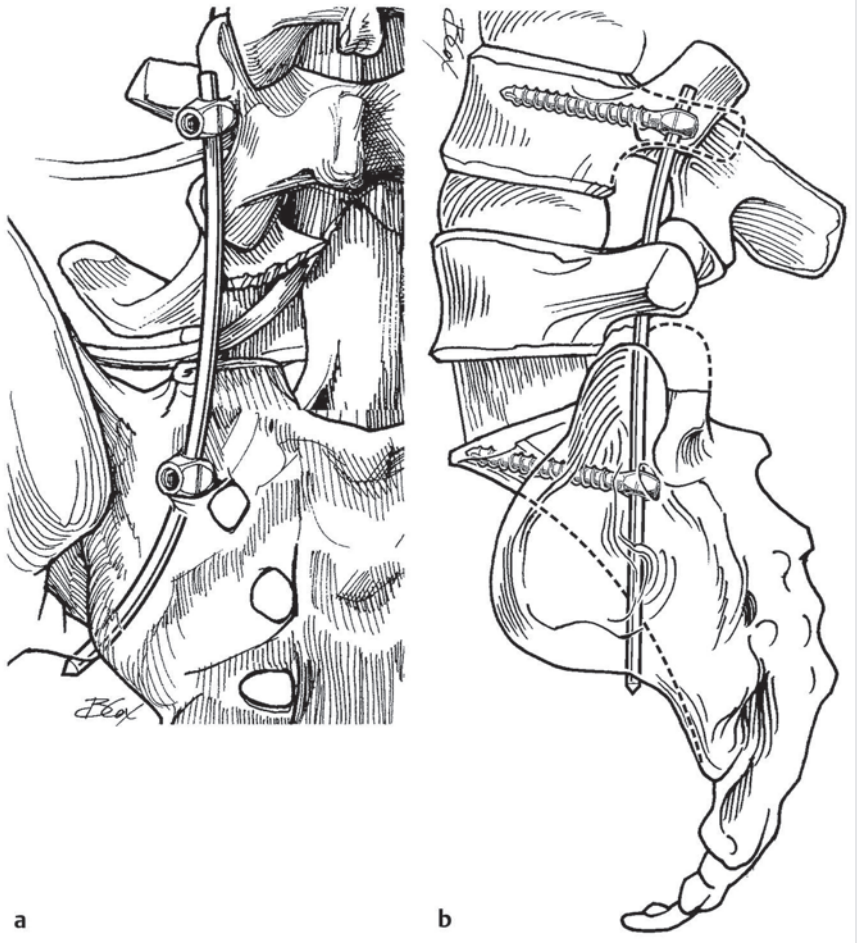

Fig. 47.4 **(a)** The sharp end of the rod penetrates the anterolateral sacral cortex. (**b**) A typical multilevel construct with insertion of the intrasacral rods distally and adjacent to the inferior sacroiliac (SI) joints.

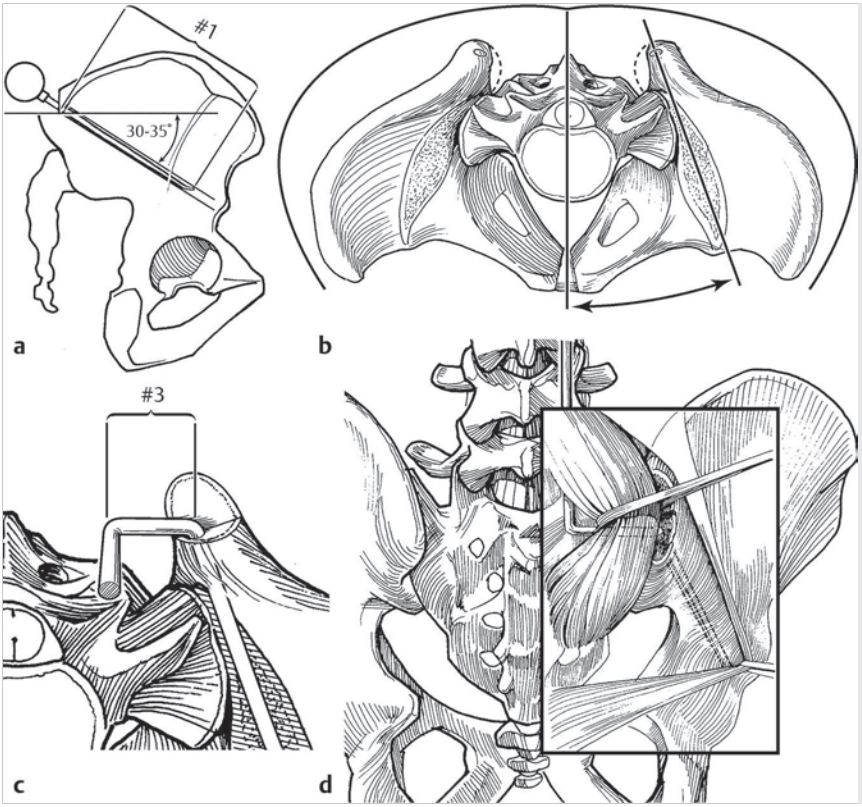

Fig. 47.5 Graphic representation of the four measurements needed to calculate bend angle and rod length when preparing a Galveston bend. **(a)** Measurement 1: Rod length and sagittal angle (to the midaxial plane) of the intrailiac segment. **(b)** Measurement 2: The transverse plane angle of the iliac fixation site to the midsagittal plane. **(c)** Measurement 3: The mediolateral distance from the iliac entry site to the intended line of longitudinal passage along the spine. (**d**) Measurement 4: The length of rod from the sacrum to the most cephalad level of instrumentation.

47.11 Bailout, Rescue, and Salvage Procedures

47.11.1 Intrasacral (Jackson) Technique

If the implants fail or loosen, a more traditional approach for insertion of the S1 screw, tangential to the sacral end plate, is still possible. The Galveston technique and other methods for more distal pelvosacral fixation can also be used at the time of revision. If significant manipulation of the lumbopelvic junction is performed, structural interbody support at L5–S1 is needed. The most likely mode of failure with intrasacral fixation is rod breakage proximal to the S1 screws. Sacral screw loosening or breakage is reduced (rarely) when the technique is performed properly. Structural interbody fusion at L5–S1 minimizes rod breakage and helps maintain lumbopelvic lordosis.

47.11.2 Galveston Technique

If iliac breach occurs during preparation, it is usually recognized with the ball probe. The most common reason for breach during preparation is an incorrect starting position or orientation. Typically, the probe is oriented too proximally. Intraoperative posteroanterior and lateral radiographs with a probe in the passageway can help to identify this, and the passageway can be probed again in the proper orientation. If the cutout occurs during rod placement, salvage is more difficult. Conversion to the Dunn-McCarthy technique of sacral ala S rod may be an option. Other options are S1 and S2 screws, iliosacral screws, and S2 ala screws, or a modified sacral bar technique.

Pitfalls

- Intrasacral (Jackson) technique: Contouring can cause indentations on the rod that can reduce the fatigue life of the implant; therefore, 6.35-mm stainless steel rods should be used. The use of polyaxial screws at L5, and perhaps L4, can facilitate the procedure .
- Galveston technique: Cutout of the iliac portion duration preparation or placement of the rod is the main complication encountered intraoperatively.

48 Sacral Screw Fixation

Chris Villar and Daniel R. Fassett

48.1 Description

The lumbosacral junction is a common location for spondylosis and other pathologies; it is one of the more common areas to place spinal instrumentation. Anatomical and biomechanical differences at the lumbosacral junction need to be considered when placing instrumentation in this area. The sacral pedicles are typically larger diameter, shorter, and composed of less cortical bone in comparison to the lumbar pedicles. As a result, sacral pedicle screws do not provide as much fixation as lumbar screws. In addition, in the presence of lumbar lordosis, the center of rotation of the L5–S1 motion segment lies ventral to the sacral pedicle; therefore, this is a biomechanical disadvantage for sacral screw fixation in comparison to pedicle screws at other levels in the spine that typically will cross ventral to the axis of rotation.

All of these issues become especially important in long-segment fusions that carry more biomechanical stress at the ends of these long constructs. Long-segment fusions crossing the lumbosacral junction have a relatively high rate of pseudarthrosis and are prone to hardware loosening. Additional points of fixation, such as pelvic instrumentation, should be considered for long-segment fusions crossing the lumbosacral junction. Fixation to the pelvis includes sacral pedicle screws, sacral alar screws, and S1 and S2 sacral-alar-iliac (SAI) screws.

48.2 Key Principles

- Sacral pedicles differ in size and amount of cortical bone in comparison to thoracolumbar pedicles.
- Sacral pedicle screws are typically sufficient for short-segment lumbar fusions.
- Sacral alar screws are an option if the sacrum promontory has been destroyed with prior pedicle screw loosening, tumors, or infections.
- Long-segment fusions crossing the lumbosacral junction are prone to pseudarthrosis and additional fixation such as sacral-alar-pelvic or other forms of pelvic instrumentation should be considered.

48.3 Expectations

Understanding of the unique biomechanical issues related to sacral instrumentation is essential in surgical decision making pertaining to instrumentation that crosses the lumbosacral junction. Balancing the risk of instrumentation failure and pseudarthrosis with the morbidity of additional instrumentation is crucial in complex spinal procedures involving the lumbosacral junction. For the safe and effective placement of sacral pedicle, alar, and sacral-alar-iliac screws, an understanding of sacropelvic anatomy is imperative.

48.4 Indications

48.4.1 Sacral Pedicle Screws

- Short-segment (less than three to four spinal levels) fusions crossing the lumbosacral junction
- May be used in long-segments fusions, but recommend additional fixation to the pelvis

48.4.2 Sacral Alar Screws

- Used as an alternative to S1 pedicle screws when there is destruction of the sacral promontory by various pathologies (tumor, infection, severe loosening of prior S1 pedicle screws)

48.4.3 Sacral-Alar-Iliac (SAI) Screws

- Long-segment fusions crossing the lumbosacral junction such as spinal deformities
  - SAI screws at S2 are often used in conjunction with S1 pedicle screws
- Short-segment fusions where there is significant stress upon S1 pedicle screws or S1 pedicle or alar screws are not feasible. Examples may include:
  - High-grade L5–S1 spondylolisthesis
  - Tumors of the lumbosacral junction
  - Infections of the lumbosacral junction
  - Complex sacral fractures
- Revision surgery for spinal deformity crossing the lumbosacral junction
  - Dual S1 and S2 SAI screws may be a viable option to salvage a previous long-segment fusion with a L5–S1 pseudarthrosis and loosening of previous instrumentation

48.5 Contraindications

48.5.1 Sacral Pedicle Screws

- When used alone, S1 pedicle screws may not be sufficient for long-segment fusions.
- Lesions destroying the sacral promontory

48.5.2 Sacral Alar Screws

- Not sufficient for long-segment fusions
- Lesions involving the sacral ala

48.5.3 Sacral-Alar-Iliac Screws

- Can be challenging in patients with congenital pelvic abnormalities

48.6 Special Instructions, Positioning, and Anesthesia

Preoperative planning is essential in cases extending to the sacrum especially when lower S2, S3, and/or alar iliac screws are being implanted. The sacral morphology across individuals may vary widely, thus obtaining computed tomography (CT) with axial, coronal, and sagittal reconstructions may be useful for preoperative planning in extremely complex cases. General anesthesia is employed in the supine position; the patient is then turned prone onto a radiolucent operating table with maximal lordosis to prevent erroneous fusion in a "flat" orientation. Assuring the patient's chest and abdomen are free of pressure points, along with ample padding of the extremities to prevent neurapraxia. When prepping and draping the patient, special attention must be taken towards the caudal prep. Depending on the extent of sacral involvement during instrumentation it may be necessary to lengthen the exposure near the gluteal cleft, which should have secure placement and coverage of the sterile (Ioban; 3 M Health Care) drape to prevent contamination from the adjacent anogluteal region.

48.7 Tips, Pearls, and Lessons Learned

48.7.1 Sacral Pedicle Screws

Sacral pedicle screws are sufficient for short-segment fusions, but are high risk for pseudarthrosis and screw loosening in longer fusions. Sacral pedicle screws are typically placed at S1 although S2 and S3 pedicle screws are possible, but do not provide much additional fixation. With the sacral pedicles being larger than the lumbar pedicles, larger diameter screws (7–9 mm) can be used in an attempt to gain more screw purchase. Medially oriented S1 pedicle screws carry the greatest bone density and stronger fixation in the sacrum. The sacrum is also one location where bicortical screw purchase can be safe and advantageous in terms of improving pullout strength. Targeting the thick cortical bone at the sacral promontory or even placing the screw into the S1 end plate superiorly can also improve fixation to help prevent screw loosening. If there is any concern about sufficient fixation at the lumbosacral junction, then pelvic instrumentation should be considered and S2 SAI screws may be a good option for additional fixation.

48.7.2 Sacral Alar Screws

There are very few instances where sacral alar screws are indicated and sufficient for stabilization. Alar screws offer little cortical purchase; therefore, they should not be used in longer-segment fusions without additional pelvic instrumentation. Given the poor strength due to lack of cortical bone purchase, alar screws are probably only indicated as standalone sacral fixation in short-segment fusions where the sacral promontory has been destroyed prohibiting a pedicle screw placement.

48.7.3 Sacral-Alar-Iliac Screws

Sacral-alar-iliac (SAI) screws can be a useful adjunct to other sacral screws to gain fixation below the lumbosacral junction with biomechanically favorable properties in comparison to sacral pedicle screws. S1 pedicle screws typically do not extend ventral to the axis of rotation, and therefore do not resist flexion moments very well. Pelvic screws, including SAI screws, allow for the greatest screw length anterior to the axis of rotation thus providing the greatest leverage to resist flexion moments.

Sacral-alar-iliac screws are an alternative to traditional pelvic screws and have a number of benefits in comparison to other screw techniques. SAI screws can be aligned with lumbar pedicle screws due to their more medial starting point, and can eliminate the need for an offset connector that is commonly used with traditional pelvic screws. There is also less tissue dissection needed to place SAI screws as the posterior superior iliac spine does not need to be exposed. In addition, by crossing the cortical surfaces of the sacroiliac joint, SAI screws should have better purchase and provide better fixation than iliac screws. SAI screws are also better protected by the soft tissues above the sacrum and helps eliminate issues of painful palpable pelvic screws in thin patients.

SAI screws can be placed safely with anteroposterior fluoroscopy to visualize the sciatic notch on the pelvis to determine the superocaudal trajectory. Some have proposed biplanar fluoroscopy or oblique views, but this is often unnecessary. Intraoperative navigation can also be used to safely place these screws and may be beneficial in osteoporotic patients as cortical bone can be targeted in the trajectory. A 4-mm drill may be used with navigation throughout the entire screw trajectory. This adjustable drill bit may range in length from 60 mm up to 110 mm. The drill technique may allow easier crossing of the dense cortical bone at the sacroiliac joint.

48.8 Difficulties Encountered

48.8.1 Sacral Pedicle Screws

As with any pedicle screw, penetration of the inferior or medial pedicle can lead to nerve root impingement or penetration of the dura. Ventral to the sacrum are the sacral sympathetic nerve trunk, middle sacral artery and vein, and even visceral organs (colon), which are at risk for injury with screws projecting significantly ventral to the anterior sacral cortex.

48.8.2 Sacral Alar Screws

Alar screws can also potentially cause visceral injury with ventral cortical breach common due to the lateral trajectory toward the internal iliac vessels.

48.8.3 Sacral-Alar-Iliac Screws

The biggest challenge with SAI screws is their placement through a relatively narrow channel of bone in the ilium. Breaches can occur medially into the pelvis, lateral into the gluteal muscles, and inferiorly into the sciatic notch. Medial breaches carry risk for visceral injury to the bowel and vascular

structures. Lateral breaches are typically of little significance, but inferior breaches into the greater sciatic notch may potentially injure the gluteal vessels and nerves, sciatic nerve, and pudendal vessels and nerves. It is possible but highly unlikely that a screw can enter the acetabulum. A well-placed SAI screw of 100 mm in length can be placed safely without violating the acetabulum.

48.9 Key Procedural Steps

In most situations, the sacral anatomy is exposed through a midline incision, although a lateral muscle-splitting approach can easily expose the entry point for pedicle screws at S1. Sacral alar and SAI screws require a midline incision for appropriate lateral angulation. Sacral pedicle screws require caudal exposure to the top of the sacrum at the junction of the L5–S1 facet complex. With their slight superior trajectory, sacral alar screws require slightly more exposure inferiorly to obtain the appropriate angulation. SAI screws are most commonly placed at a S2 starting point when they are used in conjunction with S1 pedicle screws.

The S1 pedicle screw starting point is at the junction of the sacral ala and inferolateral to the S1 facet angled approximately 20 to 30 degrees anteromedial and parallel with the end plate to achieve bicortical placement through the S1 end plate with a superiorly angled trajectory towards the promontory. A starting point is made with an awl or bur hole. The pedicle is then cannulated in the trajectory described. Prior to tapping, it is critical to assess for a pedicle breach with a pedicle-finder probe. Once comfortable for safe screw placement, the hole is tapped and the S1 screw is inserted. S1-alar screws are often placed using the same starting point as a S1 pedicle screw, but with lateral angulation ranging 25 to 45 degrees laterally. The starting point for a S1-alar-iliac screw is the lateral sacral crest between the S1 foramen and S1 superior end plate. The trajectory is approximately 40 degrees lateral and 40 degrees caudal.

S2-pedicle screw placement begins at approximately the midpoint of the S1–S2 foramina, or just cranial to the midpoint, and the medial border of the lateral crest. The trajectory is anteromedial (20–30 degrees medial, or perpendicular to the dorsal sacral surface). The S2-alar screw is directed anterolateral, beginning at the starting point for the S2 pedicle screw. However, the screw is aimed laterally 30 to 40 degrees and superiorly 10 to 20 degrees. Placement of a S2-alar-iliac screw also employs a similar starting point midway between the S1–S2 foramen at the lateral crest. The screw trajectory is approximately 40 degrees lateral and 40 degrees caudally similar to the trajectory of the S1-alar-iliac screw. As stated previously, a large adjustable (60–110 mm) drill bit 4 mm in diameter can be used to create the starter hole. Channeling an awl, pedicle probe, or cervical curette across the dense cortical bone of the sacroiliac joint may be challenging. Bouncing the drill back and forth and slowly advancing it provides a tactile sensation to let the surgeon know that they are still drilling within bone. If there is not resistance to drilling or any concerns, the drill should be removed from the starter hole and the trajectory palpated with a pedicle feeler probe. If there is still bone at the base of the hole, it is acceptable to continue drilling to a longer depth. In most spinal instrumentation systems, the maximum screw length is 100 mm and this is an ideal length for SAI screws. If a breach is encountered at a more shallow depth a shorter screw can be placed. A screw length less than 65 mm may not cross the sacral iliac joint and therefore not provide the fixation desired for a pelvic screw. In placing pedicle screws, tapping to a smaller diameter than the pedicle screw being inserted is a common practice to maximize screw purchase. However, with SAI screws there can be significant resistance due to screw length and the amount of cortical bone crossed with this screw; therefore, undertapping may not be a good option as one may break the tip of a screwdriver while placing a SAI screw. Consider tapping to the same diameter as the screw except when dealing with osteoporotic bone.

48.10 Bailout, Rescue, and Salvage Procedures

Pseudarthrosis, specifically at L5–S1, is common with lumbosacral fusions, especially longer-segment fusions. Many surgeons commonly utilize an interbody graft at the L5–S1 level to minimize the risk for pseudarthrosis at this level. Larger diameter sacral screws can be placed through the same trajectory if the degree of screw loosening is not significant. In situations of pseudarthrosis following a long-segment fusions with loosening of both S1 pedicle screws and pelvic or SAI screws, one can place dual SAI screws in the S1 and S2 trajectories to provide four points of fixation across the sacroiliac joints to maximize fixation.

Pitfalls

- The major pitfall commonly observed is inadequate fixation at the lumbosacral junction, particularly with long-segment fusion or other situations when there is high stress upon the sacral pedicle screws. It is questionable whether S1 pedicle screws alone are adequate fixation in a long-segment fusion where the lumbosacral junction is prone to pseudarthrosis.

49 Spondylolysis Repair (Pars Interarticularis Repair)

Christopher M. Bono and Andrew J. Schoenfeld

49.1 Description

This procedure entails direct bone grafting and stabilization of unilateral or bilateral spondylolytic (pars interarticularis) defects.

49.2 Key Principles

Unhealed fractures of the pars interarticularis, also known as isthmic spondylolysis, can be chronically painful despite appropriate nonoperative management. Although patients with anterior vertebral displacement (i.e., isthmic spondylolisthesis) are usually treated with arthrodesis, direct repair of the nonunion without the use of intersegmental lumbar fusion techniques may be effective in some cases of spondylolysis in the absence of frank spondylolisthesis or disk degeneration. Several techniques have been described, which have in common autogenous bone grafting of the pars defect followed by stabilization of the posterior elements. The manner of stabilization has varied as spinal instrumentation has become progressively more sophisticated. Initial reports of direct pars repair involved the use of simple wire loops. More modern constructs include pedicle screw–hook constructs, pedicle screw–interlaminar screw fixation, or the use of miniplates. Although a clear clinical advantage of one technique over another remains to be definitively demonstrated, one recent study has shown earlier return to function using pedicle screw–hook techniques. Biomechanical investigations indicate that the pedicle screw–hook construct or pedicle–interlaminar screw fixation offer the greatest stability at the site of the defect. As a basic tenet of nonunited fracture management, enhanced stability is desirable as a means to potentiate healing. In addition, some authors maintain that the use of pedicle screw-based constructs obviates the need for postoperative bracing.

49.3 Expectations

To decrease low back pain from an unhealed spondylolytic (pars) defect by maintaining motion and avoiding intervertebral fusion.

49.4 Indications

- Direct pars repair is indicated for those patients with a clearly identified, painful spondylolytic defect. Ideally, the defect should be a so-called advanced lesion (i.e., well-corticated nonunion) with poor potential for healing through nonoperative management.
- Clinically, the patient should have low back pain that is localized to the lumbosacral (L5 pars is most common) or lower lumbar region (L4 pars is second most common) without lower extremity radiation.
- The neurologic exam should be normal.
- Symptoms are typically exacerbated by extension and relieved by flexion.
- Ideally, physical examination should reveal tenderness with palpation of the spinous process of the level in question, although paraspinal tenderness over the defects themselves may also be appreciated.

49.5 Contraindications

49.5.1 Relative

- Grade I spondylolisthesis (fixed or dynamic): It is usually undesirable to perform a direct pars repair in patients with spondylolisthesis.
- Mild to moderate disk degeneration
- Patients of younger age, no evidence of displacement across the pars defect, and increased T2-weighted uptake in the area of the lesion on magnetic resonance imaging (MRI) may have a reasonable chance of healing with bracing.

49.5.2 Absolute

- Spondylolisthesis of grade II or higher
- Advanced, painful disk degeneration (pain more with flexion than extension)
- Anomalies of the posterior elements that preclude the safe placement of instrumentation (e.g., spina bifida, malformations of the spinal laminae, congenital absence of a pedicle, spinal structures too narrow to accept conventional instrumentation)

49.6 Special Considerations

- Flexion-extension radiographs should be obtained preoperatively to rule out dynamic subluxation.
- A MRI should demonstrate minimal to no evidence of degeneration, desiccation, or height loss at the involved disk space.
- Temporary pain relief from an intralesional anesthetic injection may be a prognostic indicator of a good response to pars repair.

49.7 Special Instructions, Positioning, and Anesthesia

The patient is positioned prone on a radiolucent operating table. Using a lateral view, the proximal and distal extents of the incision are marked. The superior margin of the incision generally lies at the level of the cranial facet joint (typically L4–L5 for a planned L5 repair), with the inferior extent at the superior aspect of the S1 lamina. In addition, a separate incision is marked over the iliac crest bone-graft harvest site. Alternatively, a bone graft may be harvested through the same midline lumbar incision.

49.8 Tips, Pearls, and Lessons Learned

It is important to understand the anatomy of the two fragments of the affected vertebra. The anterior fragment consists of the superior articular processes, which are connected to the pedicles and transverse processes by a small portion of the pars (proximal to the defect). The proximal fragment of the pars is contiguous with the vertebral body. The distal fragment consists of the majority of the pars interarticularis (distal to the lesion), the laminae, the spinous process, and the inferior articular processes. Depending on the underlying etiology of the defect, as well as the duration of its existence, there may be varying degrees of morphologic abnormality present in these structures. Preoperative computed tomography (CT) is generally recommended to facilitate visualization of the vertebral elements and to enable surgical planning.

49.9 Difficulties Encountered

- Adequately seating the hook at the lower border of the lamina
- Vertebral structures (pedicle or lamina) too narrow, or deformed, to allow placement of conventional instrumentation

49.10 Key Procedural Steps

49.10.1 General Technique and Bone Grafting

- After sterile prepping and draping, a midline incision is made.
- The lumbosacral fascia is incised on either side of the spinous processes. Be careful to preserve the midline interspinous and supraspinous process ligaments.
- Next, the bilateral laminae are subperiosteally exposed, with care taken to avoid injury to the facet joint capsules. The transverse processes at the level of the lesion are also dissected using electrocautery.
- A large curette, or small Cobb retractor, is used to clearly delineate the entire pars interarticularis and its defect.
- A pseudocapsule is usually present over the unhealed pars defect (▶ Fig. 49.1). This is carefully excised along its posterior aspect with small and medium-sized curettes (▶ Fig. 49.2). The anterior and medial portions of the pseudocapsule are left intact to protect the neural elements and help avoid extrusion of bone graft into the spinal canal. Once the proximal and distal surfaces of the pars nonunion are clearly identified, a high-speed 3-mm bur is used to shape them into flat, transverse surfaces. In addition, burring should expose viable bleeding bone on either side of the lesion.
- Two small cube-shaped pieces of autologous iliac crest bone are now harvested. The exact size of the graft is determined by the size of the defect, although a 1 cm × 1 cm piece is usually sufficient. The defect site should be further prepared, using the bur, to accept the dimension of the graft. The graft is then tamped gently into place to span the defect (▶ Fig. 49.3). Even without fixation, the graft should have some degree of stability due to an interference fit.

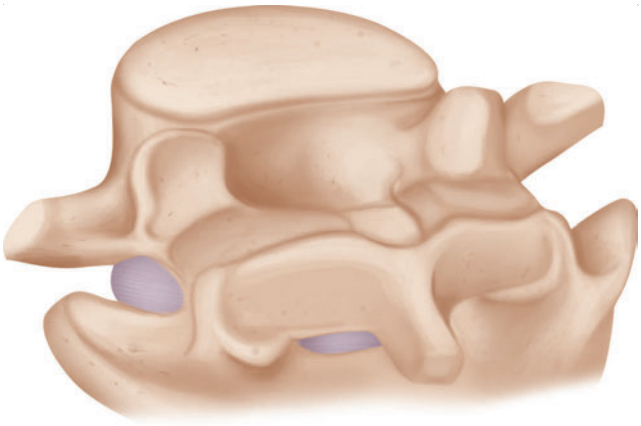

Fig. 49.1 A pseudocapsule forms around pars defect, a response of the continued motion through the unhealed fracture.

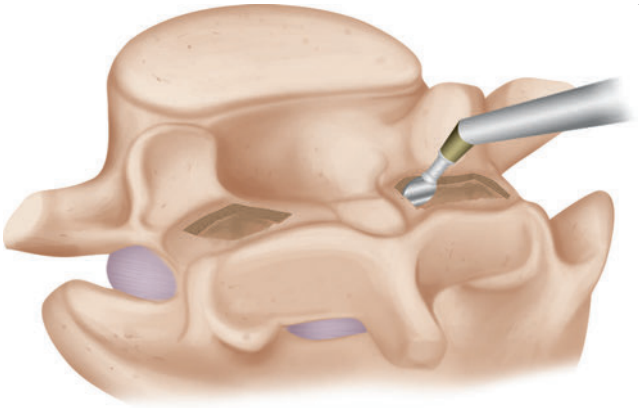

Fig. 49.2 The pseudocapsule is opened to allow the bony ends to be prepared to accept the bone graft.

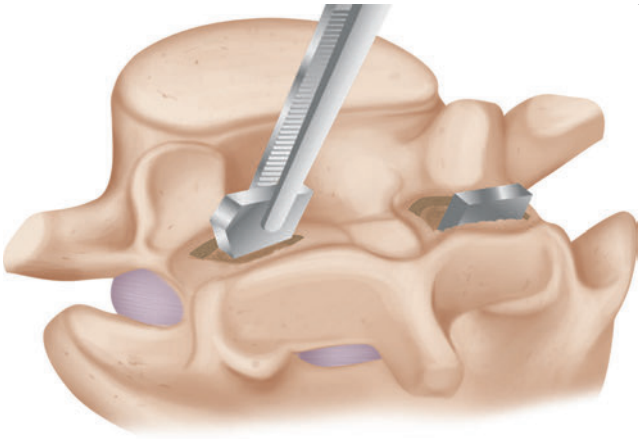

Fig. 49.3 The contoured piece of bone graft is tamped into the prepared defect site.

49.10.2 Fixation Techniques

Wire Fixation (Scott's Technique)

Wires or cables are carefully looped around the transverse processes bilaterally. These are subsequently passed around the

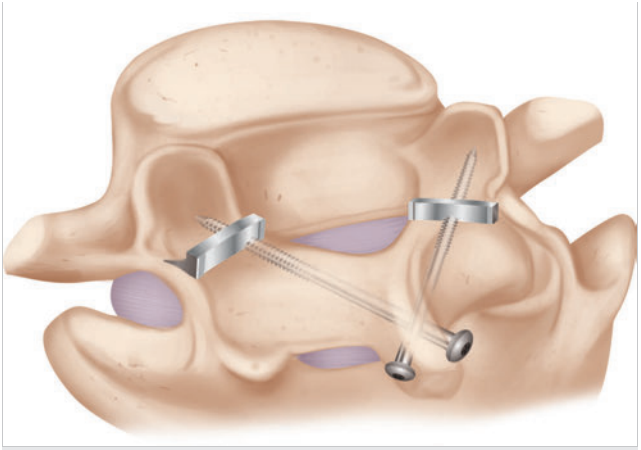

Fig. 49.4 Buck's compression screw technique.

inferior aspect of the spinous process. The wires or cables are tensioned to place a compressive force across the grafted defect.

Interfragmentary Screw (Buck's Technique)

A compression screw (i.e., lag screw) can be placed across the defect. The starting point is just inferior and medial to the pars defect. The drill is directed superior and slightly lateral to cross the defect. The screw path ends in the dense bone of the pedicle. The screw is then inserted and tightened to compress the bone graft into place (▶ Fig. 49.4).

Pedicle Screw–Interlaminar Screw Construct

Pedicle screws are placed in a conventional fashion and connected to interlaminar screws using a rod (▶ Fig. 49.5). The laminar screws are placed using a technique identical to the insertion of C2 laminar screws. These constructs have been found to be biomechanically comparable to pedicle screw–hook instrumentation and are purported to have a lower profile.

Pedicle Screw–Infraspinous Process Rod

See *Bailout, Rescue, and Salvage Procedures* section.

Pedicle Screw–Infralaminar Hook (Authors' Preferred Technique)

With the graft in place, attention is directed toward placement of the pedicle screw. For a L5 lesion, a L5 pedicle screw is placed. To avoid injury to the suprajacent facet joint, the entry site should be placed as lateral as possible (at the junction of the pars and the transverse process), with the screw angled medial toward the vertebral body. It is our preference to use a polyaxial screw, although a fixed screw may also be utilized.

After releasing the ligamentum flavum from the inferior aspect of the L5 lamina, an upgoing lamina hook is inserted close to the spinous process. Because the hook by itself has little stability (and tends to dislodge), it is our preference to loosely fix the short rod to the hook head with a locking cap. Holding the hook in place with the inserter, the proximal end of the rod can then be directed into the pedicle screw head. The locking cap is then provisionally placed into the head of the pedicle screw (▶ Fig. 49.6).

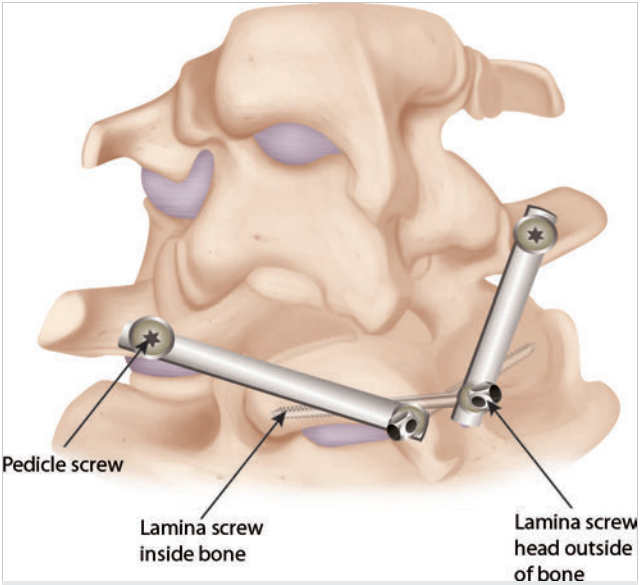

Fig. 49.5 Pedicle screw–interlaminar screw technique

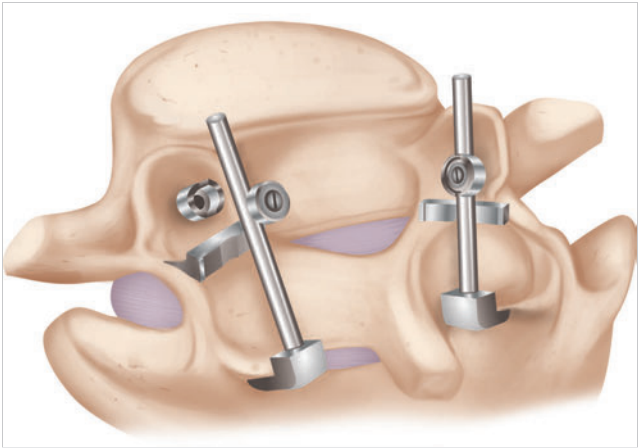

Fig. 49.6 Pedicle screw–hook technique. Trick: The hook is first attached to the short rod prior to insertion. With the hook in position, the rod is then levered into the pedicle screw head.

Next, the rod is definitively tightened to the lamina hook with a torque-limiting device. Using a compressor placed below the hook and above the pedicle screw, the graft is compressed in its position. The pedicle screw is then final-tightened. Anteroposterior and lateral fluoroscopic images are obtained to confirm implant position.

The surgical site is copiously irrigated and closed in layers using absorbable suture. The skin is closed with staples, and a sterile dressing is applied. Postoperatively, the patient remains on prophylactic antibiotics for 24 hours. Ambulation is encouraged on postoperative day 1. No brace is applied. In follow-up, radiographs are obtained at 2 weeks, 3 months, 6 months, and 1 year to monitor healing of the defect as well as positioning of the implants.

49.11 Bailout, Rescue, and Salvage Procedures

49.11.1 Intraoperative

- Depending on the extent of inadvertent facet injury, the surgeon may consider performing a facet fusion. In our experience, this is rarely necessary. If the facet joint has been badly injured, arthrodesis is recommended.
- The most cumbersome portion of the operation is securing the rod to the hook and screw. Because the rod is so short and the hook unstable by itself, we recommend fixing the hook to the rod prior to insertion. Depending on the angulation of the posterior lamina surface, the rod can preclude the necessary angle for hook insertion. In these cases, the rod can be lordotically bent to avoid this obstruction. If the hook is still too difficult to place, a single rod may be bent into a V shape, passed beneath the spinous process of L5, and connected to both screws, or interlaminar screws may be placed instead. If an infraspinous rod is used, the rod should be advanced cranially prior to final tightening to effect compression across the pars defect and bone graft.

49.11.2 Late Postoperative

- If late hook dislodgment occurs, and interfragmentary compression appears to be lost, revision surgery to replace the hook may be performed. Alternatively, a different construct, such as those described above can be used. As a last resort, posterolateral instrumented arthrodesis may be performed.
- If symptomatic nonunion persists, a posterior/posterolateral fusion with instrumentation and autograft is the preferred treatment option.

Pitfalls

- Intraoperative
  - Injury to the facet joints
  - Inability to adequately seat the hook
- Late Postoperative
  - Late hook dislodgment or failure of instrumentation
  - Nonunion

Section XI

Anterior Lumbar Decompression

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XI

50 Anterior Lumbar Surgical Exposure Techniques

Alice J. Hughes, Paul W. Millhouse, Alexander R. Vaccaro, and Ben B. Pradhan

50.1 Description

Anterior approaches to the lumbar spine have been developed for easier and more direct access to the ventral spine. Direct access for the spine surgeon implies a more efficient and thorough diskectomy or corpectomy. Today, the anterior approach frequently involves collaboration with a vascular-trained access surgeon; however, recent literature suggests that the utilization of such a surgeon does not necessarily change the types and rates of complications. An adequately trained spine surgeon can safely proceed with such exposures independently, provided a vascular surgeon is available in case of a vascular complication. Depending on the circumstances, a left-sided or right-sided (for L5–S1 only) retroperitoneal approach can be performed. The direct transperitoneal (transabdominal) approach is usually reserved for revision cases.

50.2 Key Principles

The location, orientation, and size of the incision can vary according to the location and extent of the pathology, the patient body habitus, prior anterior abdominopelvic surgeries, the nature of the spinal procedure to be performed, and the experience of both the access surgeon and/or of the spine surgeon (▶ Fig. 50.1).

50.3 Expectations

It is essential that the area of pathology be well visualized. During exposure, the abdominal and pelvic structures should be safely retracted and remain well out of place throughout the entirety of the procedure (▶ Fig. 50.2). Ideally, supplementary lighting should be available as the overhead lights are often blocked by the surgeon; this can be provided with the use of head lamps and self-illuminating retractors. It is often necessary for the surgical segment(s) to be visualized radiographically with radiolucent retractors in place. This is particularly true with some interbody or corpectomy devices, as well as with artificial disk replacements.

50.4 Indications

An anterior approach is utilized when performing an anterior lumbar corpectomy, diskectomy, or interbody fusion. These types of surgeries are typically performed for intractably symptomatic degenerative disk disease, isthmic or degenerative spondylolisthesis, adjacent segment disease, pseudarthrosis, deformity, instability, trauma, tumor, or infection.

50.5 Contraindications

An active abdominal or pelvic infection is a contraindication to anterior lumbar surgery in the same vicinity, unless the target

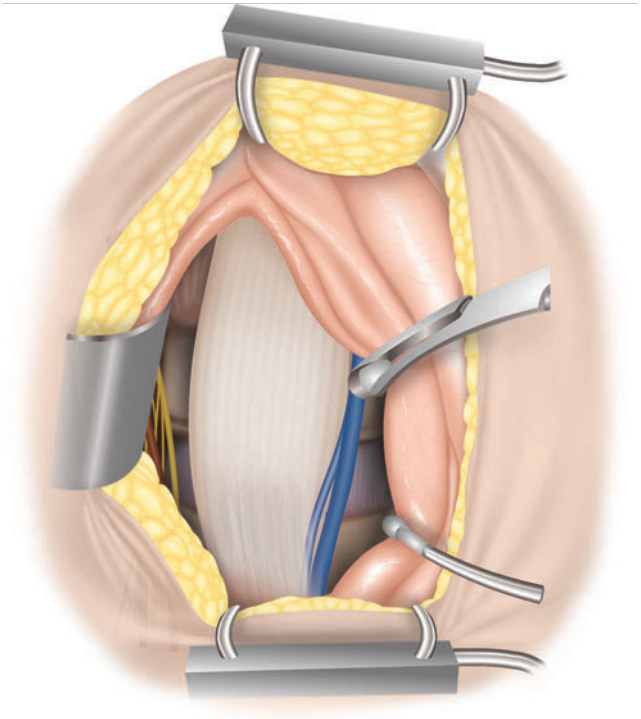

Fig. 50.1 Exposure of the L5–S1 disk space.

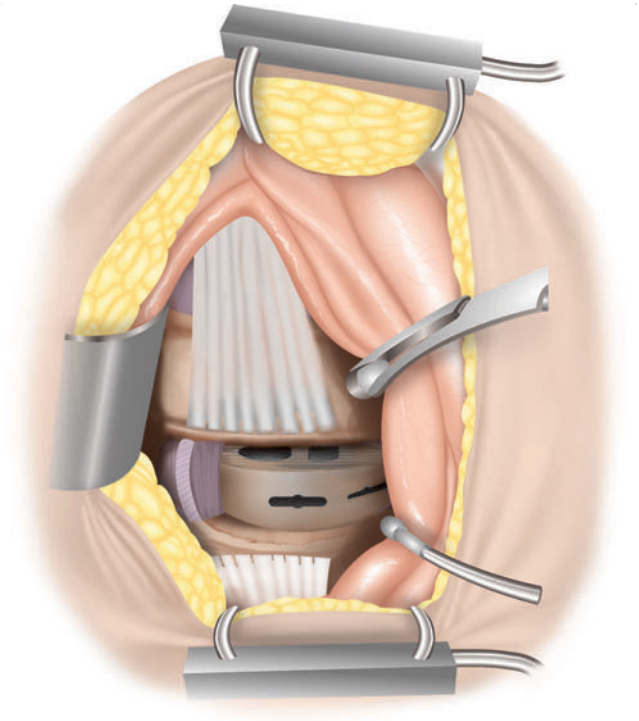

Fig. 50.2 One-level exposure with midline of disk marked (for prosthetic disk placement).

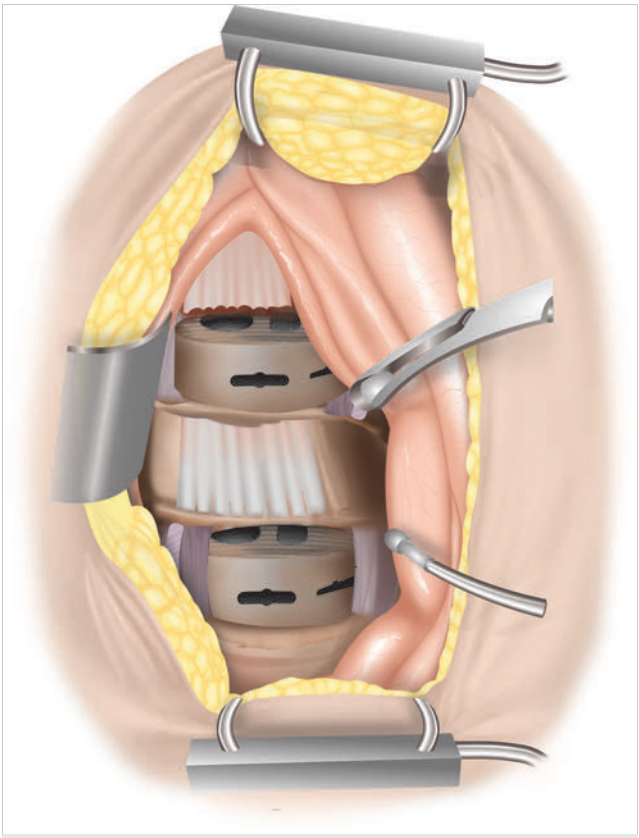

Fig. 50.3 Final view with prosthetic disk in position.

of the surgery is an infection in the spine itself. Relative contraindications include previous anterior surgery at the same operative level, osteoporosis, morbid obesity, severe atherosclerosis of the anterior blood vessels, and severe endometriosis or other pelvic inflammatory disorders.

50.6 Special Considerations

Because success of the approach is dependent upon how well the exposure is performed and maintained, a good retractor system is indispensable. A table-held retractor system is recommended, as it maintains a steady pressure (as determined to be safe by the access surgeon) on the abdominal contents, minimizes readjustments, and frees up the hands for the procedure. This is especially helpful during artificial disk replacement surgery, where a wider anterior exposure of the disk is necessary to identify the midline of the disk, perform a thorough diskectomy, restore disk height symmetrically, and elevate a contracted posterior longitudinal ligament if necessary (▶ Fig. 50.3).

We caution against the use of Hohmann retractors and Steinmann pins drilled into the vertebral bodies for retraction, as they may structurally damage the vertebra if knocked loose and their sharp tips can damage nearby tissues during placement or removal. Additionally, the acute angulation of a vessel around the pin or instrument may lead to vessel injury.

Some of the modern interbody or corpectomy devices, and all of the artificial disks, require fluoroscopic visualization during instrumentation. In these cases, a radiolucent Jackson table is recommended. As previously mentioned, proper lighting is essential when working in small operative fields such as the anterior lumbar spine. At minimum, multiple overhead lights are recommended; in addition, local visualization can be greatly enhanced by the use of head lamps, self-illuminating retractor blades, or illuminating sleeves that fit over the existing retractor blades.

It is generally advised that cell saver machinery be available for the surgery, as bleeding tends to be brisk from a vascular laceration in this area, although this is fortunately a rare occurrence with experienced access surgeons. Occasionally, clots can form or atherosclerotic plaques may break off inside a vessel, which may require additional vascular surgery, and the use of cell saver will be necessary.

A pulse oximeter on the patient's left great or second toe during surgery can provide valuable information about pulsatile blood flow through the vessels in the operative area. An alarm warns that blood flow to the extremity may be compromised. If O_2 saturation does not return to preoperative levels, an iliac artery thrombosis is assumed until proven otherwise. As there have been cases of plaques dislodging and embolizing the contralateral iliac vessel many surgeons are using pulse oximetries on both feet.

Antiemetics such as metoclopramide (Reglan, Baxter Pharmaceutical) and gastric decompression are recommended as these measures help reduce the incidence of ileus. Nasogastric or orogastric tubes may be inserted after the patient is anesthetized and removed at the completion of the procedure.

50.7 Special Instructions, Positioning, and Anesthesia

It is good practice to examine the preoperative radiographs to assess the location of the surgical level in relation to palpable anatomical landmarks such as the iliac crest or pubis. Inspection of the lateral radiograph reveals whether the bottom disk spaces are readily accessible with a good line-of-sight over the pubis, and where the incision should be made for ideal visualization of the angled disk spaces.

The exact procedure and the type of instrumentation should be discussed with the access surgeon preoperatively because the optimal type, extent, and orientation of the approach may vary. For example, for an artificial disk replacement, a symmetric anterior exposure of the disk space is required to properly center the device, whereas for a fusion, a limited anterolateral exposure may be sufficient.

The patient is positioned supine on a radiolucent table (e.g., Jackson) that will accommodate a fluoroscopy machine positioned under and across it for anteroposterior and lateral image intensification. If a regular operating table is used, it may have to be reversed head-to-toe to make intraoperative imaging possible. The arms should be abducted at approximately right angles to the body to allow adequate room for fluoroscopy machine positioning. A Trendelenburg position is reported to be helpful sometimes as it causes the abdominal structures to move in a cephalad direction, facilitating surgical access.

It is often desirable to augment lordosis in the lumbar spine for better access to the disk space with the use of a small bump under the back. If too large a bump is used, however, it can

cause the anterior vessels to drape against the anterior surface of the spine, making them difficult to mobilize. Use of an inflatable pneumatic bladder and pump is suggested as a means to accomplish this, and is adjustable intraoperatively.

Anesthesia should provide complete muscle relaxation throughout the procedure as the retractors are under tension, and loss of relaxation can cause them to become dislodged.

50.8 Tips, Pearls, and Lessons Learned

At times, optimal exposure cannot be maintained by self-retaining retractors, and a hand-held malleable retractor may be required with the help of an assistant. The surgeon must watch for tissues such as vessels or the ureter that may protrude between the retractor blades. A surgeon should hold an instrument (e.g., suction tip or surgical sponge) in the nondominant hand to retract structures from the working field while performing a diskectomy. If the protrusion of structures is excessive, or if the retractors are unstable, it is better to call this to the attention of the access surgeon or adjust them early on. If a bur or drill is involved, it should be turned on only after the working end is totally inside the disk space, and turned off and completely still before it is removed.

Retrograde ejaculation is a possible complication of this approach in males, with a reported incidence ranging from less than 2% to 10%. This risk must be discussed with patients, especially those wishing to father children, so that adequate reproductive planning or donation to a sperm bank may take place. Surgeons should use caution when cauterizing vessels as it has been reported that the incidence of retrograde ejaculation may be higher with the use of cautery in the anterior spine. For this reason bipolar cautery is probably safer, owing to less electrical arcing. The transperitoneal approach, typically utilized for revision cases, has been shown to be associated with a higher incidence of this feared complication.

To reduce the rate of retrograde ejaculation, elevate the peritoneum away from the promontory with a Kittner. The fibers of the superior hypogastric plexus run adherent to the peritoneum, much as the ureter does. Mobilize this peritoneum to the right, if working from the left at L5–S1, and then the fibers will be protected once the retractor is deployed on the right side of the spine. Other means of maintaining hemostasis (e.g., ties, clips, Gelfoam (Pfizer Pharmaceuticals), thrombin, other hemostatic agents), and blunt dissection (peanuts, laps) are also recommended.

When obtaining intraoperative radiographs, it is helpful to fill the exposed area with irrigation so as to avoid the "white-out" effect seen with air on fluoroscopic imaging.

Oval-shaped, sturdy suction tips may be useful to enter narrow disk spaces, and can also be used to lever open tight disk spaces during a diskectomy.

Specially designed disk space distractors can be used to sequentially expose the disk space, allowing for better visualization and thus an easier and more efficient diskectomy. Distractors also facilitate visualization of the posterior vertebral edges, which is necessary for complete diskectomy and when posterior longitudinal ligament elevation is needed. A typical distractor can be confined in one half of the disk space while the surgeon works in the other half, and can be switched to the other side once the first half is completed. It is advisable that one never uses the distractor in the central weaker part of the end plate, as this can cause fractures and increase the risk of subsidence of the interbody device (which is especially undesirable for an artificial disk). The distractor tips should always reach across to the posterior apophyseal ring before expansion, and fluoroscopy may be used to ensure this placement.

It may be sensible to instrument the tightest disk level first if operating on multiple levels; otherwise the surgeon may face difficultly implanting sufficiently sized devices after the other levels have been instrumented. Keep in mind the importance of minimizing the number of times the retractors are manipulated.

50.9 Difficulties Encountered

The greatest difficulty is encountered during mobilization of the great vessels, especially at the L4/5 level, where over 90% of all vascular injuries have been shown to occur. This does not tend to be problematic at L5–S1 because it is usually below the bifurcation of the great vessels.

Scar tissue resulting from a previous surgery or an active inflammatory process increases the difficulty of the dissection. Meticulous attention must be engaged in detecting all of the important anterior structures such as the bowel, vessels, and ureters. Temporary stents may be placed in the ureters prior to surgery to aid in identifying and protecting them intraoperatively.

50.10 Key Procedural Steps

The patient should be positioned supine as mentioned above (▶ Fig. 50.4). If autologous iliac crest bone graft is to be

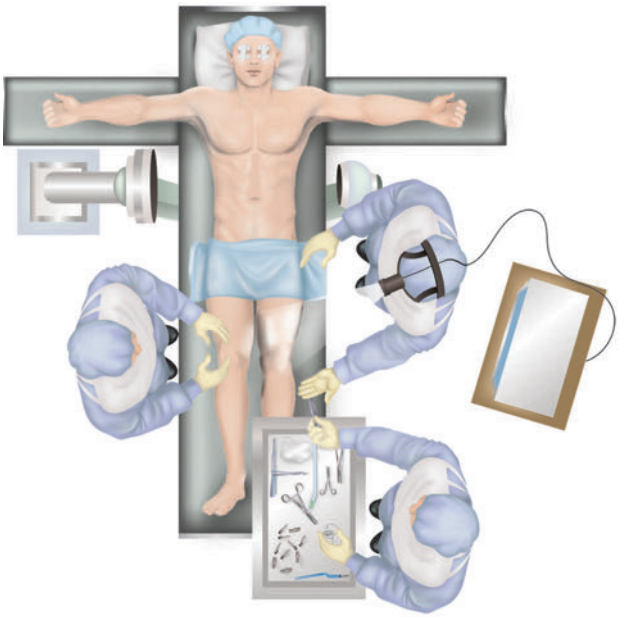

Fig. 50.4 Patient positioning, location of surgeon (with head light), assistant (across the surgeon), scrub tech, and fluoroscopy machine.

harvested, this can be done during the approach, but prior to deployment of the table-held, self-retaining retractors. Additional risk is incurred if the retractors are placed, removed for graft harvest, and then placed again.

Incision location: Fluoroscopically localized and placed transverse incisions are best for single-level cases. Oblique or vertical midline incisions are acceptable for multiple-level operations. Vertical paramedian incisions should be avoided because a larger incision is required for the same amount of exposure and there is further disruption of the retroperitoneal planes above and below the target levels, making future revision surgery more difficult (▶ Fig. 50.5).

It is generally advised that the procedure progress one level at a time. Retraction and exposure of more than one level should not be pursued unless it is easily accomplished, and only at L4/5 or above. Otherwise, excessive traction or stretch is imparted on the vessels and abdominal structures. It is better to have the retractors moved as the intervention at each level is completed.

To reduce the incidence of venous injury, ligation of the iliolumbar vein is recommended when approaching L4/5, although experienced surgeons may choose not to ligate this vessel. Observe caution when clips are used for distal control, as the iliolumbar vein courses close to the lumbosacral plexus posteriorly (▶ Fig. 50.6).

To help reduce the incidence of left iliac artery thrombosis, mobilize the external iliac artery as distally as possible. This is easily accomplished with a Kittner because the external artery has no branches except for an occasional muscular tributary to the psoas that can be clipped and transected. In this way stretching of the vessels is reduced upon placement of the retractors. Elongation of the vasculature is not well tolerated, as it may lead to microintimal tears that release thrombogenic cytokines.

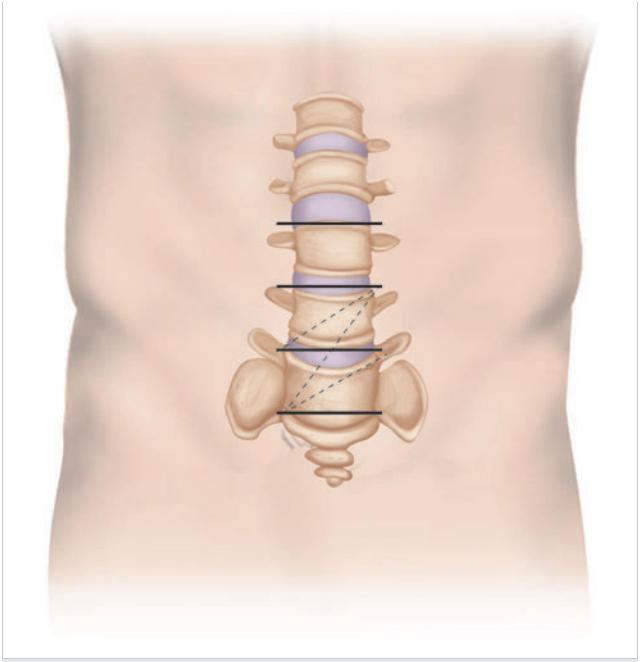

Fig. 50.5 Mapping the incisions for approaches to various levels.

50.11 Bailout, Rescue, and Salvage Procedures

The approach surgeon should be comfortable with converting the approach type intraoperatively. If a retroperitoneal approach is initiated and becomes difficult and dangerous, which can happen in revisions especially, the approach can be converted to transperitoneal. If it is discovered that only some of the planned levels are accessible through the approach, or if an unforeseen event precludes the surgeon from performing the entire procedure, alternate means of treating the spine should be planned (e.g., posterior surgery).

The access surgeon should be comfortable handling any vascular complication or event. This can range from repairing lacerations to performing thrombectomies. For instance, if an iliac vein tear requires repair with sutures, the patient may need to be anticoagulated due to an increased risk of iliofemoral venous thrombosis after these repairs. Anticoagulation measures may also be required for thrombectomy or arterial repair. The heparin should be reversed after the procedure and bridged to an antiplatelet medication such as Plavix (Bristol-Myers Squibb Pharma). Careful deep vein thrombosis (DVT) monitoring is also mandatory in these cases.

In case of disruption of a major vein, especially in an inaccessible area, an attempted repair may result in profuse blood loss and significant morbidity or mortality. In such situations one should first achieve control of the injured area with pressure. It

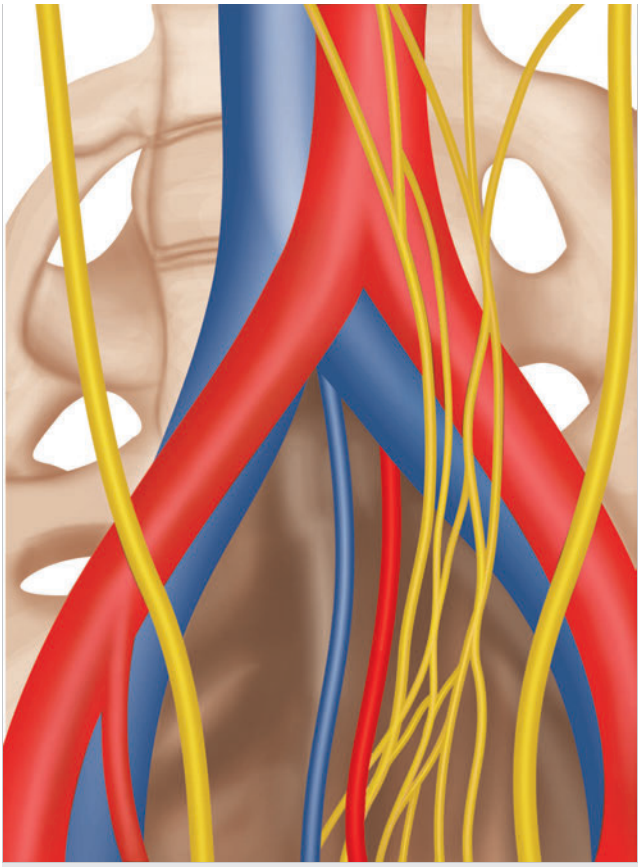

Fig. 50.6 Retroperitoneal anatomy at the anterior lumbosacral region.

may then be prudent to ligate the vessel proximally and distally, even if it means ligating the inferior vena cava and both common iliac veins; this solution is relatively well tolerated and may be an appropriate salvage procedure in the case of a massive vascular injury.

Pitfalls

- Improper incision placement can result in significant difficulty during the approach or the spinal procedure itself. A retroperitoneal approach in the setting of prior abdominal procedures can be challenging due to scarring, granulation tissue, and difficulty in identifying and preserving the peritoneum and its contents.
- Wrong-level surgery must be avoided by good radiographic visualization. The approach surgeon may find intraoperative fluoroscopy useful to confirm surgical level.
- Revision surgery should be performed only by very experienced access surgeons, as it requires thorough knowledge of soft tissue behavior following prior surgery in the area. Knowledge of the previous procedure is also crucial to plan the revision approach. If within a week to 14 days of the initial surgery, it may be acceptable to return via the same incision and approach path, whereas an alternate route is recommended if a longer period has elapsed.
- Imaging studies, such as venograms (or magnetic resonance imaging venograms), may be necessary, especially in the case of an anteriorly dislocated prosthesis at L4/5 that may be impinging on the left common iliac vein. If clots are present, an inferior vena cava filter may be inserted prior to the revision.
- In general, revisions at L5–S1 should be attempted from the opposite side of the prior approach or via a transabdominal exposure. Revisions of L4/5 are best approached either via a more lateral approach or a transabdominal route along the peritoneal reflection, lateral to the sigmoid colon. For L3/4 and L2/3, it is prudent to go lateral at a level above or below the prior approach in an effort to find undisturbed retroperitoneal planes.
- Do not attempt revision surgery from the right side except for at L5–S1. The course of the vena cava makes the risk completely prohibitive when approaching from the right.

51 Anterior Lumbar Diskectomy

Priscilla Ku Cavanaugh, Caleb Behrend, Matías Petracchi, and Alexander R. Vaccaro

51.1 Description

An anterior diskectomy through an approach that provides direct visualization of the anterior or lateral aspect of the lumbar spine is described.

51.2 Key Principles

This procedure provides an adequate exposure, safe, and gentle retraction of the great vessels and neural avoidance to allow safe and effective anterior access to the disk space.

51.3 Expectations

Complete diskectomy permits the insertion of an interbody spacer to allow either motion preservation with a device such as a disk arthroplasty, or insertion of an allograft, autograft, or cage to aid fusion. Direct debridement of a diskitis is also possible via this approach. Additionally, anterior release as part of the correction of a spinal deformity can be undertaken.

51.4 Indications

- Interbody fusion
- Corpectomy
- Nucleoplasty
- Open biopsy
- Debridement of spondylodiskitis
- Release for correction of spinal deformities

51.5 Contraindications

- Abdominal or pelvic infection
- Severe peripheral vascular disease
- Aortic aneurysm
- Anomaly of the genitourinary system
- In some cases, malignancy

51.6 Special Considerations

Depending on the indications for the diskectomy, the interbody space can be accessed through an anterior, anterolateral, or lateral window. If the procedure requires the insertion of an interbody device such as a metallic cage, synthetic graft, arthroplasty, or nucleoplasty, the recommendations of the manufacturer should be closely followed. There are various interbody spreaders that help to open the disk space when performing the diskectomy. Usually, a wide resection of the disk and precise preparation of the end plate are necessary. This permits optimal release of the interspace and adequate contact of the interbody device with the vertebral end plate surfaces. Resection of posterior osteophytes or the posterior longitudinal ligament may be required by some implants.

Special care should be taken to preserve or restore the size of the disk space, which can be evaluated by measuring adjacent healthy levels. Evaluation of the sagittal vertical axis, local sagittal alignment, and coronal balance is crucial in preoperative planning to prevent iatrogenic imbalance following the procedure. In general, fusion or motion preservation implants are available in a variety of sizes with regards to footprint, anterior to posterior height, and angle, which aid the surgeon in achieving desired spinal alignment.

51.7 Special Instructions, Positioning, and Anesthesia

Patient positioning on the operating table can facilitate or hinder the ease with which the diskectomy procedure is performed. Ideally, the operative level should be positioned over the "break" in the table so that the disk space can be opened up by changing the angulation of the table at the level of the break. This can aid in both preparing the disk space and inserting the interbody device. Placing a padding roll under the sacrum can aid in making the L5/S1 disk space more accessible. A radiolucent table should be used to allow intraoperative imaging. The arms of the patient can be appropriately padded and secured at the side or abducted. Special attention should be paid in order to avoid traction on the brachial plexus. Preoperative imaging can ensure adequate intraoperative radiographic quality and be used to identify the appropriate area for the incision in a projection with parallel end plates. After the approach, but before starting the diskectomy, lateral and anteroposterior spinal imaging should be performed to confirm the disk level and locate the midline of the disk space. During the diskectomy, tilting the table toward the surgeon, proper illumination, and magnification loupes are essential to adequately visualize the disk and work comfortably. If an interbody rigid device is to be placed, the table should be replaced in a neutral position after spacer insertion, and the position of the device should be checked using X-ray or fluoroscopy. Be sure that the device is well aligned in the frontal and sagittal planes with adequate restoration of lumbar lordosis and without evidence of iatrogenic imbalance (▶ Fig. 51.1).

51.8 Tips, Pearls, and Lessons Learned

Proper patient positioning is crucial and permits good intraoperative visualization of both the disk space and end plates in addition to adequate radiographic imaging. Combining the use of self-retaining and hand-held retractors further facilitates disk space visualization. Long curettes and rongeurs are useful to perform the diskectomy. Finally, spreaders help to distract the space during the diskectomy.

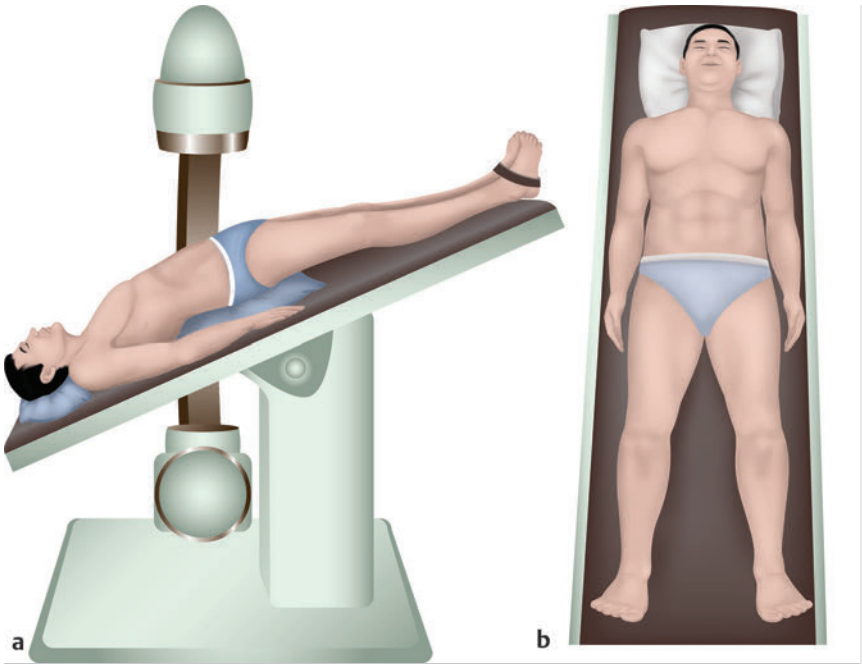

Fig. 51.1 **(a)** The patient is positioned supine with a bolster under the pelvis to allow proper visualization. The steep Trendelenburg position is both desirable and beneficial. To avoid migration during the procedure, the patient must be stabilized. (**b**) The same patient as seen from above.

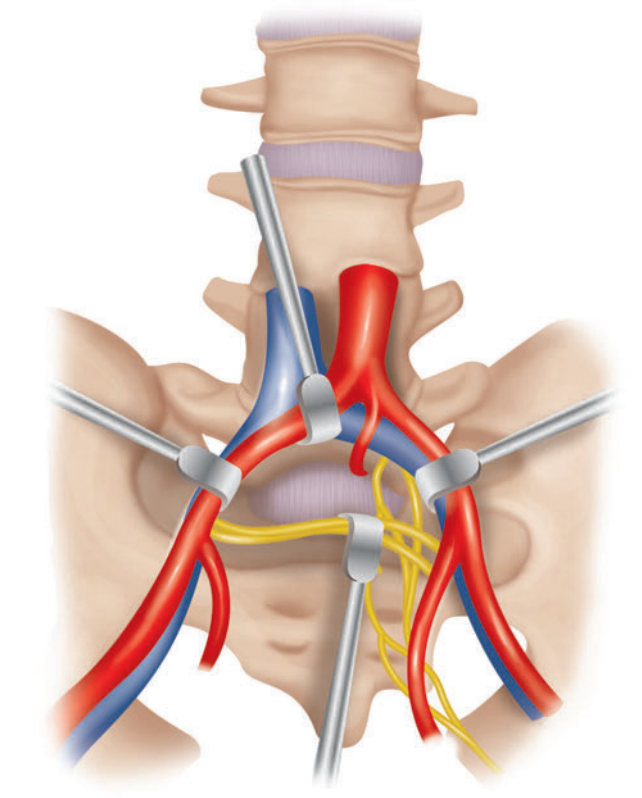

Fig. 51.2 The exposure and pin or blade retractors used for L5–S1 within the bifurcation of the iliac vessels.

51.9 Difficulties Encountered

Proper localization and initial disk resection can be complicated if the level to be treated has osteophytes. A spinal needle is used to confirm the level. In some cases, an osteotome or rongeur may be used to remove anterior osteophytes to better identify the disk space. After the majority of the disk has been resected, it is important to evaluate the residual disk located on the opposite side of the approach. Interbody spreaders help to distract the space during the diskectomy and permit a better evaluation of the remnant disk. Small curettes, a Woodson, dental elevators, a nerve hook, or ball-tip palpators are all valuable tools in evaluating the opposite side of the disk space.

51.10 Key Procedural Steps

Adequate visualization of the disk space requires retraction of the vasculature. Proximally, this is easier to achieve with a left-sided retroperitoneal approach as the aorta is more readily retracted. Prior to the diskectomy, retraction of the paraspinal structures is required. The presacral plexus of nerves, the genitofemoral nerve, and the sympathetic chain should be preserved. The presacral plexus runs vertically across the L5–S1 disk space, superficial to the middle sacral artery and veins (▶ Fig. 51.2). The genitofemoral nerve lies on the psoas muscle and exits the muscle belly at the level of L3. The sympathetic chains are in close proximity to the vertebral bodies, located medial to the psoas muscle. They can be mobilized by blunt dissection. Avoid dissecting directly over the presacral plexus prior to its mobilization, particularly cutting transversely across them or using cautery (especially unipolar). Injury may lead to autonomic dysfunction manifested in males as retrograde ejaculation. If the disk has to be resected through an anterior window proximal to the great vessels bifurcation, the vascular structures should be mobilized laterally to the opposite side of the approach (▶ Fig. 51.3). At the area distal to the great vessel bifurcation each vessel can be mobilized to its own side. To permit mobilization of the great vessels, it is sometimes necessary to ligate and divide the adjacent segmental vessels, the iliolumbar vein (L4–L5 disk space), or the middle sacral artery and vein (L5–S1 disk space). Vessel retraction can be done using a protected pin, retractor blade, or a combination of both.

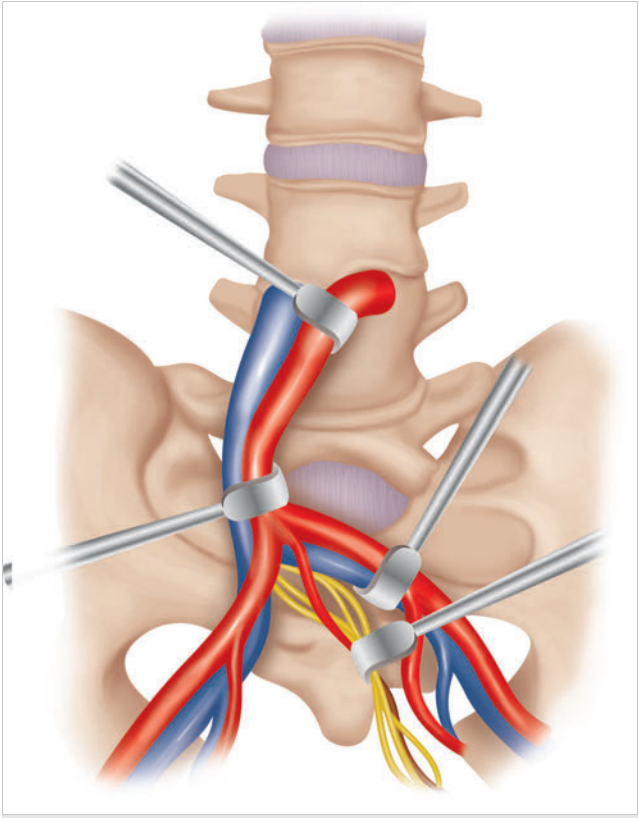

Fig. 51.3 The position of the pin or blade retractors and retraction for L4–L5 and above, with the aorta and the vena cava retracted laterally.

If small perforating veins are present in the disk space, they can be cauterized as necessary with bipolar electrocautery and divided.

The extent of disk resection and which ligaments should be divided depend on several variables including the approach utilized, indications for surgery, and the specific interbody implant or graft utilized. The anterior longitudinal ligament (ALL) and the anterior anulus can be preserved or minimally resected in the anterolateral approach to the disk. However, it can be divided, elevated, and restored later if a direct anterior approach is utilized. If arthrodesis is the indication, the goal should be to remove the complete disk and cartilage to increase the area available for fusion. Deformity correction requires a release of structures including the ALL and the complete anulus. Additionally, the size, design, and purpose of the interbody device can be used as a guide in deciding how much intervertebral soft tissue must be removed. For example, for most cylindrical cage systems partial diskectomies may be sufficient. On the other hand, some disk arthroplasty devices require extensive detachment of the surrounding soft tissue prior to inserting the device.

The diskectomy begins with an annulotomy using a small no. 15 blade. The anulus is incised parallel to the end plates. A window or bilateral flaps of the anulus can be performed. The flaps of the anulus can later be utilized to protect the adjacent structures during the diskectomy. Calibrated instruments are used to continually allow consideration of depth. A narrow, sharp Cobb elevator is used to continue with the separation of the disk from the end plates using the sharpened side toward the end plate. Angled and straight biting pituitary rongeurs are utilized to continue with the diskectomy as far back as the posterior anulus. Long curettes (straight, curved, ring) are additional instruments useful in removal of residual disk material in preparation of the end plates. Care should be taken not to disrupt the subchondral bone of the end plates during preparation. Immediate or late graft subsidence can result if the end plates are disrupted.

For collapsed disks or to aid in debridement, disk space distraction can be performed initially using wide Cobb elevators, followed by a laminar spreader or by specially designed interbody spreaders. Intraoperative imaging can be used to assess distraction and depth penetration with handheld disk space distractors relative to the dimensions of the vertebral body. Trials are used determine final implant/ graft selection.

If necessary, a bur can be used to partially decorticate the end plates to enhance the fusion or make a planar surface if it is required by the implant.

51.11 Bailout, Rescue, and Salvage Procedures

Dural tears and epidural bleeding are difficult to control because of the lack of visualization and limited exposure of the dorsal aspect of the interbody space. Control of bleeding is performed with the appropriate use of electrocautery; hemostatic agents such as thrombin-soaked sponges, Gelfoam (Pfizer Pharmaceuticals), FloSeal (Baxter Healthcare), or bone wax; and vessel ligation.

An anterior dural tear is difficult to repair by direct suture, and free muscle, a fascia graft, fibrin glue, or a combination may be attempted. Placement of a lumbar subarachnoid drain may be necessary.

If a radiculopathy occurs after the procedure, consider a possible epidural hematoma, malposition of the interbody prosthesis or graft, or retropulsed disk material that may have been pushed backward into the canal during spacer placement. Neurapraxia from tension-related injury to the nerve may also be responsible.

Pitfalls

- Approach-related complications include great vessel injury, anterior spinal artery ischemic syndrome, distal venous thrombosis, arterial embolus, urogenital complications, retrograde ejaculation with injury to the sympathetic nerves, superior hypogastric plexus lesion, genitofemoral or ilioinguinal nerves injury, and bowel injury.
- The most judicious approach is injury avoidance by employing an experienced access surgeon who is able to limit approach-related complications and assist in management if these complications should occur.
- Complications during the diskectomy include wrong-level surgery, retropulsed remnant of disk material, neurologic injury, dural tear, and epidural bleeding.
- Complications during the postoperative period include deep vein thrombosis, pulmonary embolism, epidural hematoma, spondylodiskitis, urinary retention, bowel herniation, obstruction, and ileus.

Section XII

Anterior Lumbar Arthrodesis and Instrumentation

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XII

52 Anterior Lumbar Corpectomy via a Minimally Invasive Lateral Approach

William D. Smith, Gregory D. Schroeder, and Kyle T. Malone

52.1 Description

Nonendoscopic less-invasive approaches for thoracolumbar corpectomy are increasingly being used as modern techniques and technologies have advanced. Additionally, the use of direct visualization minimizes the learning curve and procedural adoption challenges common to endoscopic corpectomies. One such technique, the mini-open lateral approach for thoracolumbar corpectomy has developed from the extreme lateral interbody fusion (XLIF; NuVasive, Inc.) technique developed in the late 1990s and early 2000s and introduced into the literature in 2006.

52.2 Key Principles

Using knowledge of lateral approach anatomy and an understanding of minimally invasive exposure techniques, the mini-open lateral approach allows for a safely performed anterior corpectomy. This is most relevant for cases of traumatic spinal cord injury where emerging research suggests that early decompression is favorable to delayed or staged decompression. In treating spinal tumors, the less-invasive nature of the mini-open lateral exposure allows for a surgical treatment option in patients who are immunocompromised and would not otherwise tolerate open exposures, while also facilitating a hastened return to postoperative adjuvant therapies.

52.3 Expectations

The mini-open lateral approach, unlike less-invasive posterior approaches for thoracolumbar corpectomy, has a similar exposure orientation to the vertebral column as the open thoracotomy approach. To perform a mini-open lateral corpectomy, one should first be proficient and comfortable with the lateral transpsoas approach. This includes an understanding of regional anatomy (neural, vascular, diaphragmatic, as well as retroperitoneal, retropleural, and transpleural spaces, etc.), and being comfortable working orthogonal (90 degrees lateral) to the disk space, using advanced neuromonitoring modalities integrated into the approach and working through an access portal (split-blade retractor).

52.4 Indications

Indications for use of this approach include any disease requiring corpectomy from approximately the T5 vertebra (limited by the scapula) inferiorly to the L4 vertebra (potentially limited by neural anatomy). For traumatic pathologies or tumors extending to the posterior segments, a combined anterior (lateral) corpectomy with vertebral body replacement and posterior approach for decompression and fixation can be used. If the lesion is isolated to the anterior column only or anteriorly as well as within the ipsilateral posterolateral bony anatomy and without instability requiring posterior instrumentation, the lateral approach alone may be used (▶ Fig. 52.1).

52.5 Contraindications

Contraindications to the approach include disease at any level not approachable using the mini-open lateral approach (upper thoracic or lumbosacral levels). Other relative limitations to the use of the mini-open lateral corpectomy include treating patients with lumbar disease who have bilateral retroperitoneal scarring (e.g., bilateral kidney surgery) that limits development of the retroperitoneal surgical corridor (although retroperitoneal fat tends to limit actual retroperitoneal scaring), patients with anomalous vascular anatomy interfering with the lateral approach, and patients in whom neural anatomy (lumbar plexus) obscures the lateral transpsoas approach corridor in the lumbar spine.

52.6 Special Considerations

When performing any surgery through a mini-open lateral approach, significant bleeding can be difficult to stop. When performing a corpectomy for metastatic disease thought a mini-open lateral approach, one must be concerned not only about vascular bleeding, but also bleeding from the tumor. Prior to resecting a tumor through this approach, arterial embolization is mandatory. Additionally, this approach should not be used for highly vascular tumors such as renal cell cancer, as even with preoperative embolization, hemostasis can be difficult with these tumors.

52.7 Special Instructions, Positioning, and Anesthesia

The patient is placed in a true lateral decubitus position, confirmed orthogonal to the floor, with the table break at approximately the level of the pathology with a slight table break, if needed, for improved exposure access (rib spreading in thoracic cases, movement of the iliac crest inferiorly in lower lumbar cases). For anesthesia, muscle relaxants and paralytics cannot be used in order for electromyography (EMG) to be reliable. If muscle relaxants are required for induction, fast-metabolizing muscle relaxants should be used and the case should not proceed until an EMG twitch test is confirmed. If spinal cord monitoring is to be performed, total intravenous anesthesia (TIVA) must be used. Additionally, as the procedure uses a split-blade retractor in the thoracic spine either retropleurally or in a semi-contained transthoracic corridor, dual-lumen intubation is not required.

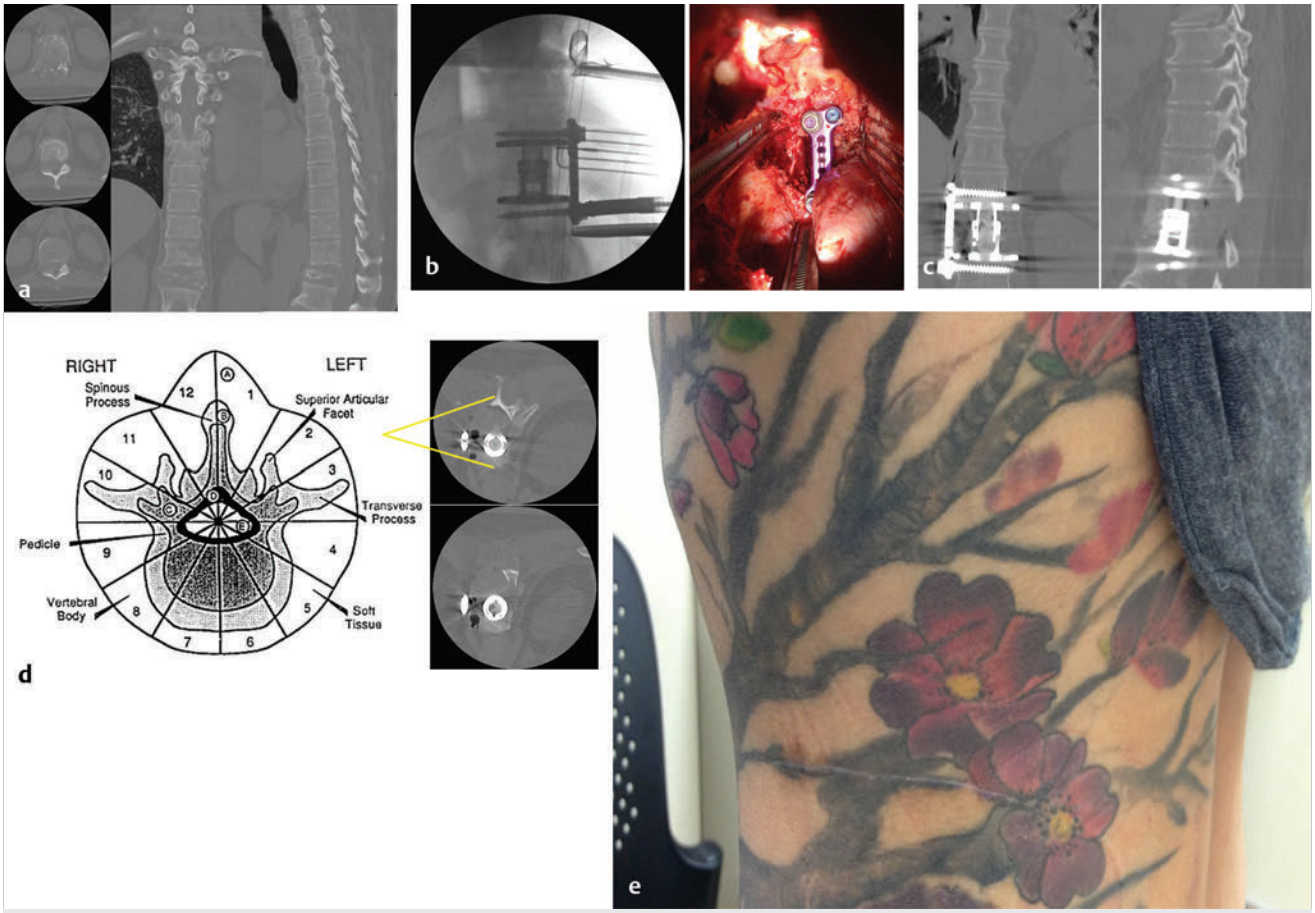

Fig. 52.1 Preoperative computed tomography (CT) showing T11 metastasis in the vertebral body and pedicle (**a**) treated with a retropleural approach for lateral corpectomy, laminectomy, and facetectomy, **(b)** followed by placement of wide-footprint expandable cage with anterolateral plating **(b, c).** Postoperative axial CT shows area of decompression (approximately zones 4 through 11 on the Weinstein-Boriani-Bagini Scale [WBB Scale]) available through the mini-open lateral approach for corpectomy, with 270-degree exposure through the lateral incision (yellow lines indicating potential field of exposure) **(d). (e)** Postoperative cosmesis following mini-open lateral corpectomy.

52.8 Tips, Pearls, and Lessons Learned

Of utmost importance is that surgeons should not attempt a mini-open lateral corpectomy without having first had adequate experience in performing a lateral interbody fusion.

Preoperative planning involving critical review of the axial magnetic resonance imaging (MRI) to assess the location and integrity of vascular, muscular, and bony anatomy is necessary to anticipate the feasibility of the lateral approach at each level to be treated. This involves an analysis of any anatomical variations in the patient (e.g., transitional levels) and evaluation of a potentially more favorable side to the approach based on anatomy.

A true 90-degree lateral position of the patient (orthogonal to the floor) must be confirmed fluoroscopically and use of a working channel orthogonal to the floor is critical to avoid migration into anterior or posterior structures, particularly on the contralateral side of the segment.

In thoracic cases, identification of the location of the head of the rib with respect to the pedicle on sagittal MRI or computed tomography (CT) preoperatively will be useful as a landmark for adequate decompression of the thecal sac during the pediculectomy (▶ Fig. 52.2).

Frequently for tumors and trauma, normal anatomy at the level of pathology can be pathologically distorted. In these cases, the use of a lateral intraoperative fluoroscopic projection showing the retractor positioned so that the great vessels are confirmed anterior and neural structures posterior of the retractor will guide protection of these sensitive structures when working in an orientation 90 degrees to the floor (▶ Fig. 52.3). Similarly, to the extent possible, parallax errors in fluoroscopy should be eliminated.

Monopolar cautery should not be used, as thermal injuries, particularly to superficial neural structures (subcostal, ilioinguinal, iliohypogastric), are possible during the initial exposure. Thus, bipolar cautery is advised.

In some deformity corrections, a complete circumferential release must be performed by completely resecting the anulus and anterior longitudinal ligament (ALL) at one level to allow for adequate curve reduction. In these cases, great care should be taken during the resection of the ALL due to the location of the great vessels anteriorly. As such, a specialized small retractor blade can be placed to define the corridor dorsal to the great vessels and ventral to the ALL. Caution with this approach

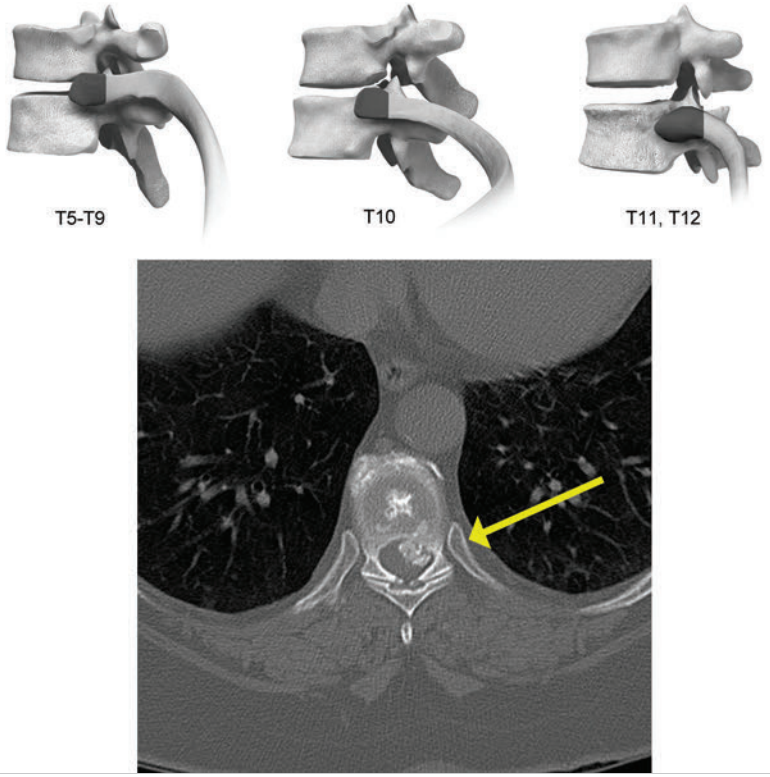

Fig. 52.2 Illustration of the position of the rib head with respect to the epidural and posterolateral disk space from the upper thoracic to lower thoracic levels (top row). Axial computed tomography showing the position of the rib head for preoperative evaluation and determination of the relationship between the pedicle and the rib head. Also, this preoperative view can assist in determining the extent of proximal rib dissection needed for control of the epidural space.

should be used in patients with prior abdominal surgery, particularly a prior anterior lumbar interbody fusion (ALIF), as adhesions between the great vessels and ALL may have developed.

Care not to injure the contralateral segmental artery should be used. If this occurs, complete exposure and identification of the segmental artery are required for coagulation and ligation. Do not attempt simple tamponade, as bleeding may persist into the retroperitoneal space and could develop into life-threatening hemorrhage.

Careful preparation of the end plates, without violation, is important for maintenance of the integrity of the end plates and potential avoidance of implant or graft subsidence.

Meticulous hemostasis must be achieved, particularly in the lumbar levels, as subpsoas hematomas can be very painful and result in transient or permanent plexopathies.

In thoracic cases, if the parietal pleura are violated but no air leak is identified, a red rubber Valsalva technique can be used to expel all excess air out of the thoracic cavity. To do this, a red rubber catheter is placed with one end in the thoracic cavity with a purse string suture placed around its exit hole and the other end of the catheter submerged in a small bowl of water. A Valsalva maneuver is then performed and held until all the air is expelled, noticeable by when air bubbles cease. The red rubber catheter is then quickly removed and the purse string suture secured (see **Video 52.1**). By avoiding an unnecessary chest tube, patient mobilization is much more rapid, reducing perioperative morbidities, most notably deep vein thromboses and pulmonary issues.

Finally, at thoracic levels, care should be taken during closure not to suture the neurovascular bundle, as this can lead to severe intercostal neuralgia. It is preferable to coagulate and cut the bundle than to put a suture loop around it.

52.9 Difficulties Encountered

Anatomically, difficulties include the limited ability to treat disease at the far superior and inferior regions of the thoracic and lumbar spine, respectively. Specifically, upper thoracic levels are generally not accessible with this approach as are lower lumbar levels. L4 cases are challenging because of the greater size of the transpsoas exposure needed while still protecting the lumbar plexus posteriorly. One must have proficiency with psoas muscle and plexus retraction where, at this level, the psoas muscle will be substantially larger and the lumbosacral plexus may be more anterior.

From a technical standpoint, the depth of the wound has a tendency to make control of a high-speed drill difficult. In tumor and traumatic lesions, osteotomes and rongeurs can be commonly used to expedite the procedure and reduce blood loss. For finer work, though, placement of a suction tip between the drill and important anatomical structures can reduce the risk of kick back.

52.10 Key Procedural Steps

After bony exposure, the surgical steps are similar to conventional thoracotomy steps.

In the thoracic spine, a section of rib can be dissected and excised, protecting the neurovascular bundle, to facilitate exposure into the thoracic cavity (▶ Fig. 52.4). This intercostal corridor should be developed so that soft tissues do not fight the retractor when decompressing the spinal cord directly; thus, proper placement of the retractor is critical. The surgeon must be able to control the head of the rib and the proximal rib to perform an appropriate decompression. Preoperative imaging

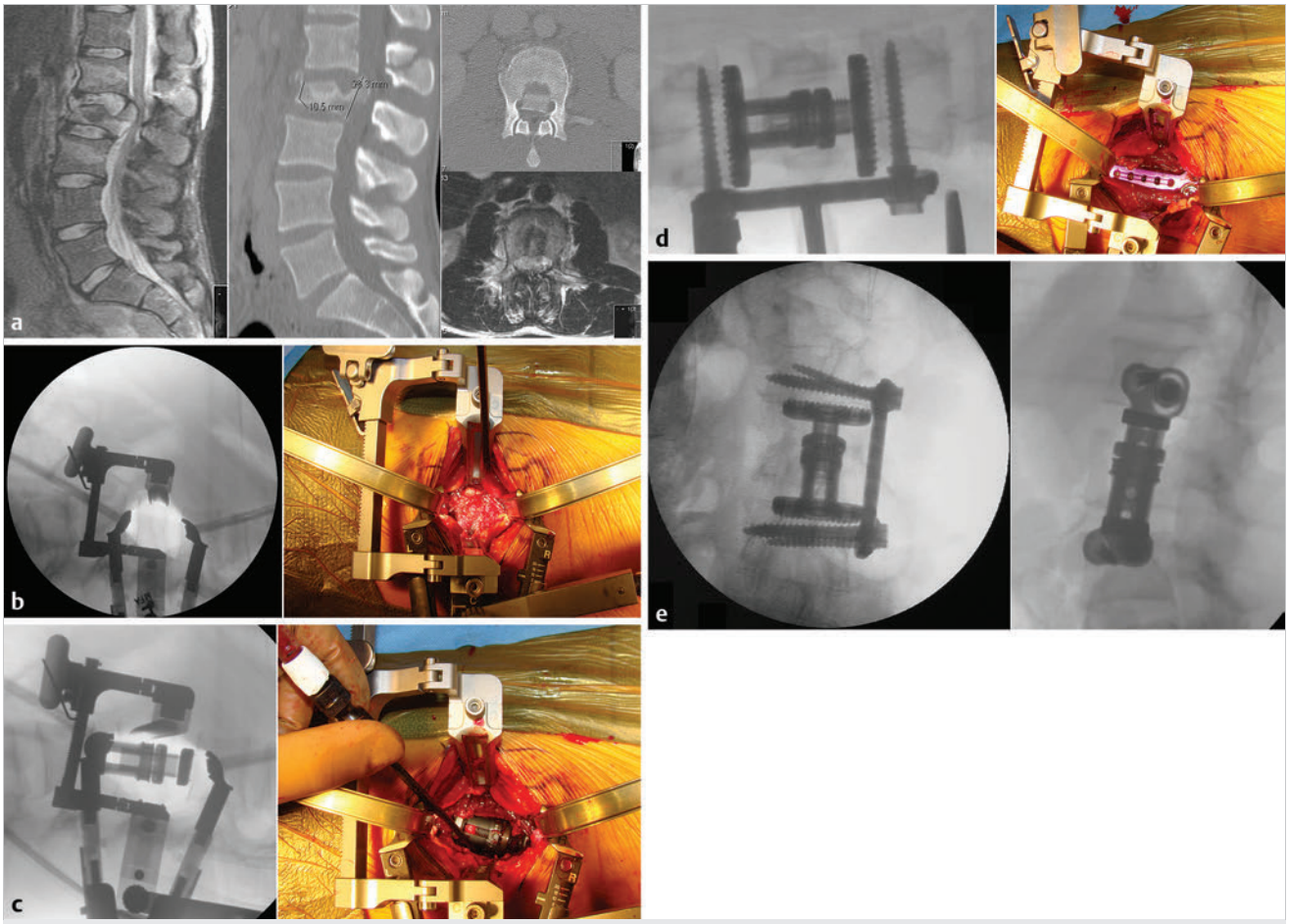

Fig. 52.3 Sagittal magnetic resonance imaging and computed tomography showing (**a**) L2 burst fracture and a fall with gross instability and neurologic impairment. (**b**) Next, lateral intraoperative fluoroscopy (left) and photograph (right) showing MaXcess retractor access to the index level for a mini-open lateral corpectomy. (**c**) Then, lateral fluoroscopy (left) and photograph (right) showing placement of a wide footprint expandable cage for vertebral body replacement. (**d**) Next, anterior fluoroscopy (left) and photograph (right) showing placement of a wide footprint expandable cage for vertebral body replacement and anterolateral plate. (**e**) Finally, anterior (left) and lateral (right) immediate postoperative fluororadiography showing a wide-footprint expandable titanium cage and anterolateral plating.

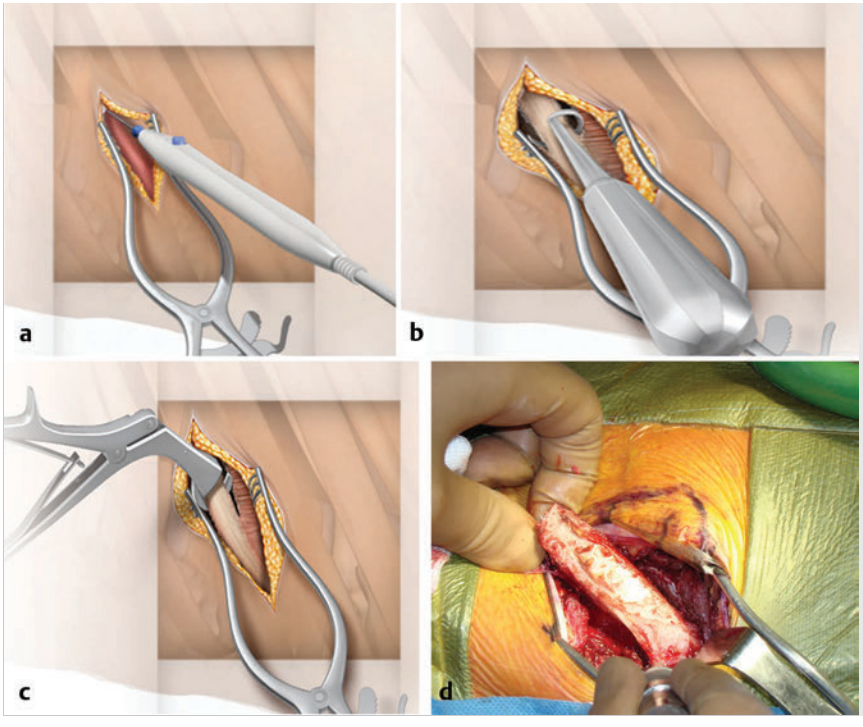

Fig. 52.4 (a-c) Illustrations and (**d**) intraoperative photograph showing initial incision and rib removal for mini-open lateral corpectomy exposure in the thoracic spine and at the thoracolumbar junction.

will provide information on the location of the head of the rib. Adherence, intraoperatively, to AP fluoroscopy will define the surgical corridor so long as one is lateral to the medial pedicle border (▶ Fig. 52.5). Once the pedicle border is thinned out with a high-speed drill, the remaining medial cortex can be removed with a thin-footed Kerrison rongeur. This will open up the lateral thecal sac and allow for a more complete and reproducible decompression of the epidural space.

As a surgeon gains experience, more aggressive bony removal can be performed through this approach alone. For instance, in broader lesions, one may eventually become comfortable excising the ipsilateral pedicle, lamina and spinous process from the lateral approach alone (▶ Fig. 52.1 d). Thus, 270-degree control of the pathology is possible through a single exposure.

Upper lumbar levels will generally require a transthoracic approach.

For treatment at the thoracolumbar junction, careful dissection of the diaphragm can be performed for preservation. At the thoracolumbar junction and in lower thoracic levels (T11 and T12), a retropleural approach can be used, avoiding the need for a chest tube (▶ Fig. 52.6). In this case, careful development of the retropleural plane and confirmation of pleural integrity are essential to avoiding postoperative pulmonary morbidity.

In the lumbar spine, a standard mini-open lateral transpsoas approach technique should be used, including careful development of the retropleural space and EMG-guided passage through the psoas muscle to the lateral aspect of the anterior spine. In lower lumbar cases, one should limit psoas and neural retraction as much as possible to limit the risk of injury to the neural structures.

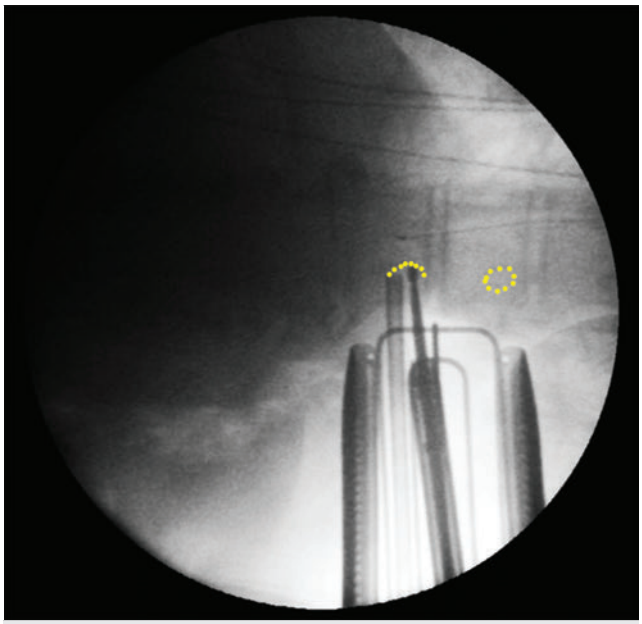

Fig. 52.5 Intraoperative anterior fluoroscopy showing decompression of the epidural space during a mini-open lateral corpectomy with a high-speed drill working lateral to the medial border of the pedicle (indicated in yellow).

52.11 Bailout, Rescue, and Salvage Procedures

One major concern with less invasive procedures is injury to the great vessels. If a great vessel tear occurs, it is a theoretically simple maneuver to extend the surgical incision anteriorly to expose the vascular anatomy. Once exposed, digital pressure can be immediately applied or a clamp can be used on the vessel until repair can be achieved.

Injury to the segmental vessels can be avoided with identification of the vessels before corpectomy. If segmental artery injury occurs and psoas muscle retraction is lost, it is difficult to identify the bleeding artery through the psoas muscle while maintaining safety to the plexus.

In patients with compromised bone quality, posterior pedicle screw and rod fixation may be considered to avoid implant subsidence.

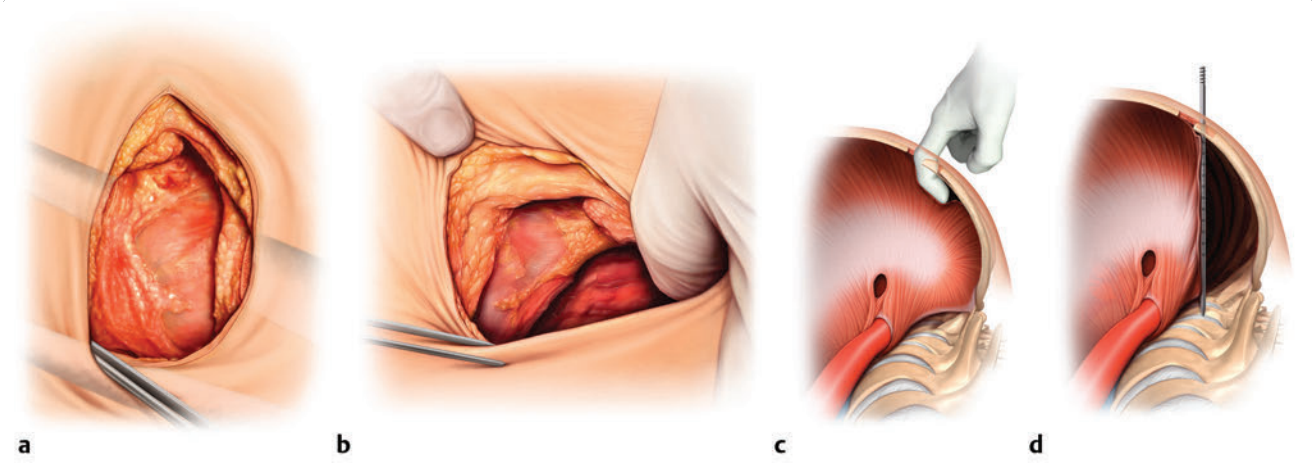

Fig. 52.6 Illustrations showing a retropleural exposure and dilator placement from **(a)** the initial exposure, **(b, c)** deflection of the diaphragm, and **(d)** anterior column access using sequential tubular dilators.

Pitfalls

- With transpsoas approaches, particularly for corpectomy, transient side effects of the approach will likely include upper thigh or groin sensory changes or pain and/or hip flexion weakness on the side ipsilateral to the approach. This is due to the fact that the psoas muscle will be traversed three times during the course of a lumbar corpectomy, once each for the superior and inferior diskectomy and then once for the corpectomy and vertebral body replacement. Generally, symptoms resolve in the early postoperative period, although some may persist.
- One pitfall of the approach is the tendency to quickly retract the psoas muscle. This can amplify postoperative sensory changes and hip flexion weakness. As such, psoas muscle retraction should be performed gradually, with time taken to perform what work can be done at the disk levels during each step of slow retractor expansion.

53 Anterior Lumbar Interbody Fusion (ALIF)

David T. Anderson and Jeffrey A. Rihn

53.1 Description

Anterior lumbar interbody fusion (ALIF) is performed using the anterior retroperitoneal or transperitoneal approach. The disk space is exposed and the disk is completely removed. An implant is impacted into the disk space to distract the end plates, create anular tension, indirectly decompress the neural foramina, and accomplish a bony fusion of the disk space. Autogenous bone graft, allograft, or bone morphogenetic protein is used to increase the fusion rate. The ALIF procedure can be performed as a stand-alone construct or as part of combined anterior and posterior procedure.

53.2 Expectations

The ALIF exposure allows for complete removal of disk material while avoiding the morbidity associated with an open posterior approach. The anterior exposure allows for a larger implant with greater surface contact area with the end plates when compared with smaller, posteriorly placed interbody implants. Theoretically, there is less risk of subsidence and higher fusion rates. The use of recombinant human bone morphogenetic protein 2 (rhBMP-2) increases the fusion rates while avoiding the morbidity associated with autogenous bone graft harvest. A successful fusion can be expected in over 90% of cases when combined with a posterior stabilizing procedure, or when rhBMP-2 is used in conjunction with an anterior stand-alone construct.

53.3 Indications

Indications include lumbar degenerative disk disease, anterior column support in long fusion constructs, restoring lordosis in deformity correction, spondylolisthesis, pseudarthrosis following posterior lumbar fusion, lumbar fusions at high risk for non-union, and infection (i.e., diskitis). Relative indication includes revision of failed total disk arthroplasty.

53.4 Contraindications

Contraindications include multilevel diskogenic back pain, spinal canal pathology, osteoporotic bone, vertebral body fracture, and pathologic processes (e.g., infection or tumor) that compromise the vertebral body end plate and requires a complete or partial corpectomy). Relative contraindications include prior retroperitoneal abdominal surgery, severe peripheral vascular disease with calcific vessels, and morbid obesity. Young males have a 2 to 5% risk of retrograde ejaculation following ALIF surgery. This may be increased with the use of BMP.

53.5 Special Considerations

Caution should be used when performing ALIF in osteoporotic bone to avoid disruption of the end plates and subsequent subsidence of implant. Care should be taken to completely remove the degenerated disk and meticulously prepare the end plates for improved fusion rates. Stand-alone constructs with integrated plates, a femoral ring allograft augmented with posterior percutaneous pedicle screw fixation, and the use of rhBMP-2 in cages can help to improve fusion rates and increase stability. Young males should be counseled regarding the risk of retrograde ejaculation. In patients with significant vascular disease and calcified vessels on radiographs, great care should be taken when mobilizing the vessels and exposing the disk space. Pulse oximetry should be used on the great toes to monitor perfusion to the feet during retraction of the common iliac vessels. Surgery performed for diskogenic back pain referable to degenerative disk disease is controversial and outcomes are less predictable than for leg pain. Other treatment options include posterior intertransverse fusion, transforaminal or posterior interbody fusion, and direct lateral interbody fusion (although this is usually not feasible at the L5–S1 level), all of which are covered in other chapters.

53.6 Special Instructions, Positioning, and Anesthesia

Carefully inspect the preoperative lateral radiograph to ensure access to the L5–S1 disk space is feasible. A high sacral slope may render full access difficult. Also, a low abdominal incision may be required to obtain proper trajectory to the L5–S1 level. The surgeon may want to check the level of the incision with a quick lateral fluoroscopic image before making an incision. The use of a vascular surgeon for the approach may be helpful, depending on the surgeon's training and expertise.

An operating room table that can rotate side-to-side is helpful for visualization when accessing the disk space. The patient is placed supine on a radiolucent table when approaching the lower lumbar levels. A bolter can be used to accentuate lumbar lordosis as needed. The patient's upper extremities should be placed in an abducted position on arm boards to allow intraoperative C-arm imaging. When approaching the upper lumbar levels, the patient can be positioned in a "sloppy" lateral position to allow for an oblique left-sided incision. The use of a radiolucent table will allow for intraoperative fluoroscopy.

53.7 Tips, Pearls, and Lessons Learned

Smooth-edged retractors should be used to avoid inadvertent injury to the great vessels. Proper illumination is of great importance in the deep abdominal cavity. Many retractors now have fiberoptic lighting. Otherwise, be sure to use a headlight. Always use fluoroscopy or radiographs to avoid wrong-level surgery. Blunt dissection and bipolar cautery should be used to sweep the tissue off of the anterior disk space to minimize the

risk of injury to the superior hypogastric plexus and subsequent retrograde ejaculation (i.e., in male patients). Any anterior osteophytes should be removed to display more normal anatomy and ensure midline removal of the disk material. After a box anulotomy is performed with a scalpel, a Cobb elevator should be used to detach Sharpey's fibers from the superior and inferior end plates. A large portion of the disk can then be removed in one piece. Careful end plate preparation is important. On the other hand, violation of the end plate must be avoided to prevent subsidence. Sequential dilation of the disk space provides the needed distraction to ensure a good implant fit and restoration of disk space height. If the disk space is very collapsed, a laterally placed paddle dilator can be used to distract the disk space and allow for adequate disk removal and end plate preparation. If using a femoral ring allograft, an AO cancellous screw with a washer can be placed in the anterior part of the inferior end plate to minimize risk of anteropulsion of the graft.

53.8 Difficulties Encountered

An improperly placed incision can make instrumentation difficult due to poor trajectory. When incising the disk, maintain the sharp edge of the blade away from the great vessels. When entering and exiting the disk space, maintain awareness of the location of the vascular structures; they can easily slip under the retractors. Certain implants (e.g., stand-alone cages, anterior plates) require screw placement in specific implant locations and at preset angles. It is sometimes very difficult to place all of the screws in the implant due to the location of the vascular structures. The surgeon should be familiar with the implant and the required screw positions, angulation, and typical sizes prior to the surgery.

53.9 Key Procedural Steps

53.9.1 Approach/Exposure

The anterior retroperitoneal approach is often used at the L5–S1 level, which is below the bifurcation of the great vessels. A transverse or longitudinal incision is made, dissection carried out through the anterior rectus sheath and the transversalis fascia. The retroperitoneal cavity is dissected bluntly and the abdominal contents are pulled toward the midline in a left to right direction. The iliac vessels can be palpated. The anterior aspect of the L5–S1 disk space is typically inferior to the common iliac bifurcation, and therefore sits between the left and right common iliac vessels. At the L5–S1 level, the middle sacral artery and vein (▶ Fig. 53.1), which typically run perpendicular to the disk space, should be identified and ligated. At the L4–L5 level, the aorta and iliac vessels should be mobilized left to right. The left iliolumbar vein should be dissected and ligated. This allows greater mobilization of the left common iliac vein (▶ Fig. 53.2).

The anterolateral approach through a left-sided oblique incision can be used for the L2–L5 levels. Above the bifurcation of the great vessels, the aorta and vena cava are mobilized left to right to expose the anterolateral disk space. Again, the left iliolumbar vein should be dissected and ligated.

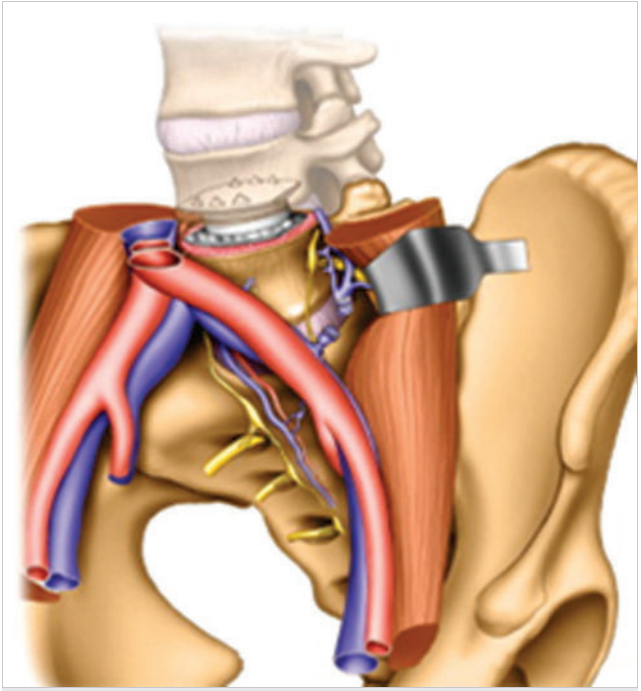

Fig. 53.1 A diagram depicting the approach to the L2–L5 levels. After the retroperitoneal plane is developed, adequate exposure of the disk spaces requires that the iliolumbar vein is ligated, this allows for greater mobilization of the iliac vein in a left to right fashion.

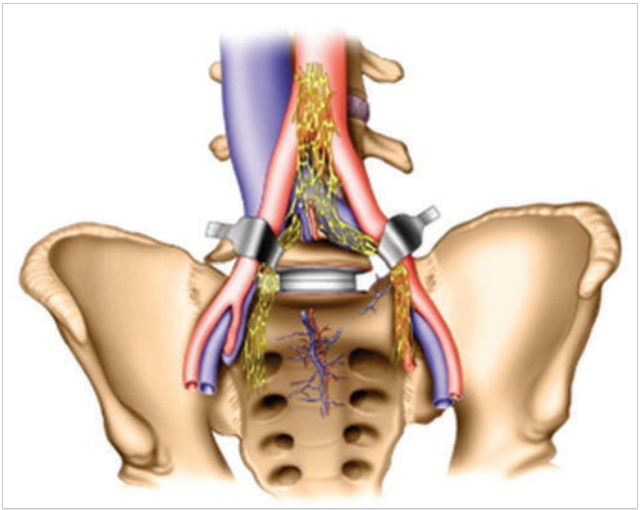

Fig. 53.2 A diagram depicting the approach to the L2–L5 levels. This level is typically approached in a retroperitoneal fashion. The anterior aspect of the L5–S1 disk space sits between the left and right common iliac vessels. To gain adequate exposure, the middle sacral vessels that run in a vertical direction over the disk space need to be ligated and the superior hypogastric plexus of nerves needs to be bluntly dissection from medial to lateral.

53.9.2 Disk Space Preparation

When performing the diskectomy, the plane between the subchondral bone and the cartilaginous end plate should be properly developed with a Cobb elevator. Sharp curettes should be used to expose bleeding bone. End-plate shavers are also

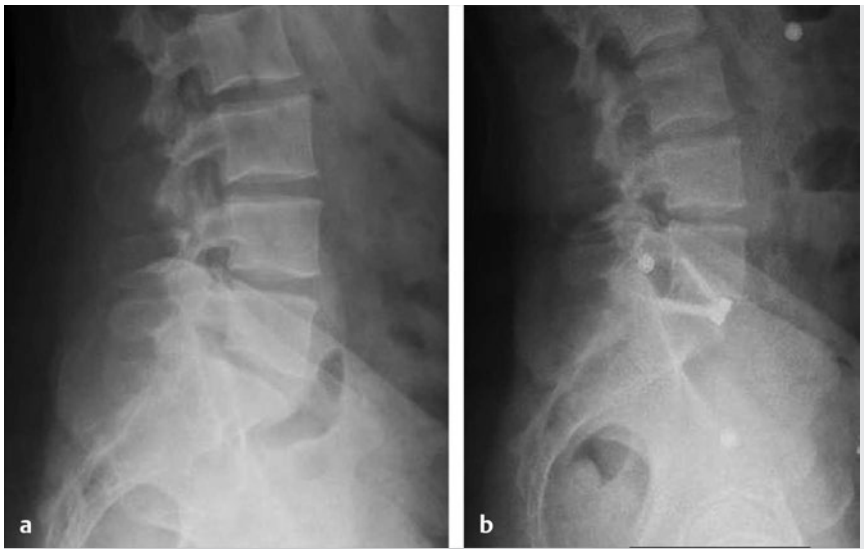

Fig. 53.3 **(a)** Preoperative lateral radiograph of a 40-year-old female patient with diskogenic low back pain and a positive diskogram at L5–S1, who had failed extensive conservative treatment. (**b**) Postoperative lateral radiograph demonstrating a solid fusion one year following an anterior lumbar interbody fusion using a stand-alone polyether-etherketone (PEEK) interbody device with screw fixation and recombinant human bone morphogenetic protein 2 (rhBMP-2).

Fig. 53.4 **(a)** Preoperative lateral radiograph of a 52-year-old male patient with a grade I isthmic spondylolisthesis with back and bilateral leg pain. (**b**) Postoperative lateral radiograph following anterior lumbar interbody fusion using recombinant human bone morphogenetic protein 2 (rhBMP-2) and a femoral ring allograft. To provide additional stability, pedicle screws and rods were placed posteriorly at L5–S1 through a minimally invasive approach.

commonly used to expose bleeding end plate bone. Paddle dilators of progressive heights are placed in the disk space and rotated to achieve distraction, segmental lordosis, and indirect foraminal decompression.

53.9.3 Insertion of Implant

The implant should be placed parallel to the end plates and seated a few millimeters deep to the anterior margin of the adjacent end plates. Be sure to check fluoroscopy for proper alignment. There are several implants available in varying shapes, sizes, and composition; allograft, titanium, and polyetheretherketone (PEEK) implants are most commonly used. Whether using cylindrical cages, femoral ring allograft, or trapezoidal synthetic cages, the surgeon needs to be familiar with the instrumentation used to insert the implant (▶ Fig. 53.3).

53.10 Bailout, Rescue, and Salvage Procedures

In the event that the implant fractures during implantation, replace with a new one. If the implant is not easily removed, hyperlordosis of the patient on the surgical table may facilitate removal. A femoral ring allograft can be removed piecemeal with an osteotome or bur. Posterior percutaneous pedicle screw instrumentation can be used to augment the construct if there is a concern regarding the stability of the anterior implant (▶ Fig. 53.4).

Pitfalls

- Incomplete diskectomy can result in retropulsion of disk material into the canal or can make it difficult to adequately place the anterior graft or cage device.
- Overaggressive impaction of the implant can cause vertebral body fracture, breakage of the implant, and/or injury to neural elements.
- Inserting the implant at an angle not parallel to the end plate may result in violation of the end plate, possible subsidence, and loss of lordosis.
- Injury to the great vessels may require the assistance of a vascular surgeon for repair.
- Injury to the hypogastric plexus can cause retrograde ejaculation.
- Injury to the sympathetic chain can cause edema and dysautonomia of the ipsilateral limb.
- Small implant size or improperly seating the implant can cause dislodgment, subsidence, or pseudarthrosis.
- Improper closure of the fascial layers can result in a hernia.
- If an incidental durotomy is encountered, it may be very difficult to repair with suture given the limited access to the thecal sac from the disk space. In this case, place a nonsuture collagen matrix (e.g., DuraSeal [Covidien]) or hydrogel sealant (e.g., DuraSeal) over the defect. Keep the patient on flat bed rest for 24 to 48 hours. If there are persistent headaches, a subarachnoid lumbar drain can be placed percutaneously and maintained for 3 to 4 days to allow the dura to heal.

54 Placement of an Anterior Stand-Alone Interbody Cage with Integrated Screw Fixation

Cristian Gragnaniello, David Robinson, Remi Nader, and Kevin Seex

54.1 Description

Anterior lumbar interbody fusion (ALIF) with cages with incorporated screws represents a single incision technique that reduces the need for further posterior supplementation with posterior fixation devices such as pedicle screws or interspinous devices.

54.2 Key Principles

This technique uses the standard principles of ALIF, but as the cage has incorporated screws no additional plate is required. The additional anterior column support makes this construct biomechanically comparable to an anterior cage and plate construct, but with less external profile. It offers an alternative to 360-degree constructs without disturbing the muscles and soft tissue posteriorly, thereby preserving the posterior tension band (see **Video 54.1**).

Although not proven to be more or less beneficial than ALIF cage and plate constructs, the lower profile at L4/5 avoids having plates immediately under major vessels. The exposure of the vertebral bodies required for their placement is also less than in ALIF cage and plate constructs.

54.3 Expectations

- Restore lordosis, foraminal and disk height.
- Allow for restoration of lateral and posterior tension bands sparing the posterior elements and paravertebral musculature.
- Enhance fusion by generous disk removal and wide-surface end-plate preparation.
- Around 70% of patients can expect a satisfactory clinical outcome with a high rate of fusion.
- Screw fixation through the cage that is biomechanically comparable to cage and plate fixation.

54.4 Indications

- Patients with mechanical back pain and imaging demonstrating degenerative disk disease, who failed conservative treatment including, but not limited to, physiotherapy, oral analgesics, and attempts at lifestyle changes.
- Painful pseudarthrosis after posterolateral fusion of posterior lumbar interbody approaches (posterior lumbar interbody fusion [PLIF], transforaminal lumbar interbody fusion [TLIF]) with failed conservative treatment measures
- This technique may be used in selected patents with spondylolysis without slip.

54.5 Contraindications

- As for other anterior lumbar interbody cages, this procedure is contraindicated in cases of active infection and spinal tumors.
- Known vasculopathy or visibly calcified aorta and iliac vessels increase the risk of vascular injury particularly at L4/5 and above where vascular retraction is greatest.
- Spinal fractures at the levels to be stabilized/fused
- Osteoporosis increases the risk of subsidence for this construct; it should be considered a relative contraindication.
- Spondylolisthesis and known instability represent a contraindication to stand-alone ALIF with cages with incorporated screws, but this technique can be augmented with posterior fixation.

54.6 Special Considerations

- Revision surgery of a disk space previously operated on by ALIF carries approximately a 50% risk of vascular injury. It is recommended to avoid if at all possible and use posterior approaches.
- In primary surgery on the L5/S1 disk, a right-sided retroperitoneal approach is suggested as this leaves the left side for any future surgery on upper segments. In very obese patients and revisions, a transperitoneal route may be preferred to avoid difficult peritoneal mobilization.
- It is generally recommended to only use a left-sided retroperitoneal approach for L4/5 and above; either side may be used at L5/S1.

54.7 Special Instructions, Positioning, and Anesthesia

- Left great toe pulse oximetry can be used to monitor for iliac artery occlusion in the left-sided anterior lumbar approaches, although it does not have absolute sensitivity it may allow for earlier detection of vascular injury. Loss of signal early in the procedure may be indication for anticoagulation to reduce risk of occlusion.
- Cell saver is important particularly at L4/5 because of the risks of vascular injury and major blood loss.
- The patient, supine on a radiolucent table, with the arms spread out in a cruciform fashion to help with X-ray access and visibility. The legs are placed in stirrups. This is the so-called Da Vinci position. For the surgeon to stand between the legs, we position the patient with the perineum at the lower edge of the table.

- Attention is placed to position the legs without stretching the hip joints, with a slight flexion of the hip to avoid compartment syndromes. Above L4/5, surgeons generally stand on the left. The bladder is catheterized.
- Vascular instruments should be available in the room to be readily opened if necessary. In particular following exposure of the segmental vessel to be ligated, there should be a choice of different-size Ligaclips and different-length applicators.
- If a vascular surgeon is not directly involved with the case, it is important to ensure there is a vascular surgeon available, preferably in the building, should there be a vascular injury.
- Prior to placing the skin incision for an L5/S1 disk it is important to get both a lateral and AP x-ray as the angle of the disk may vary considerably and at times may be projecting under the symphysis pubis, which creates difficulties with cage insertion and screw insertion into the L5 body.
- Preoperative magnetic resonance imaging is essential to assess disk pathology and may be complemented by computed tomography (CT) to clarify potential pars defects and standing flexion/extension views to assess presence of instability. A bone density scan should be considered.
- An approach surgeon may be essential or useful depending on the spine surgeon's training and medicolegal climate.
- Vascular studies are helpful particularly in the elderly to predict need for vascular mobilization.
- Requirements include large diskectomy tools, an interbody cage, and bone graft substitutes or allograft.
- Retractors are essential and usually reflect the access surgeon preferences.
- Loupe magnification with a headlight is usually sufficient for this procedure, but a microscope can be used when exploring the posterior aspect of the disk space and for foraminal decompression.

54.8 Tips, Pearls, and Lessons Learned

- The ureter can be stented in revision cases or in patients with a history of infection/inflammatory diseases.
- In finding the retroperitoneal plane and avoiding entering the peritoneum, especially in thin patients, it is easier to start the dissection through the retroperitoneal fat into the pelvis. Once found, the psoas is followed up and the medial structures are exposed.
- Disk removal and careful end-plate preparation is key to successful fusion. Inadequate disk removal and end-plate preparation will predispose to pseudarthrosis, whereas end-plate injury predisposes to collapse. Both larger cages and screws offer some protection against collapse.
- Anterior lumbar interbody fusion in the elderly is more hazardous and generally not recommended over 65 years of age. However, the L5/S1 level can be approached after a vascular study (e.g., CT angiography) has confirmed absence of severe arterial disease, and the position of bifurcation of great vessels relative to disk space. In approximately one-fifth of cases, the bifurcation of the great vessels is located below or at the level of the disk space, requiring mobilization of the left common iliac vein and artery, which could be disastrous if the vessels are calcified.
- After disk mobilization, alternating distraction of the left and right sides of end plates with thin spreaders or shims is useful to maintain distraction to allow disk preparation and foraminal decompression.
- Complete removal of the posterior longitudinal ligament and posterior anulus allows for easy height restoration; however, to gain lordosis, leaving the posterior anulus may encourage the bodies to fishmouth, with a lordotic implant achieving maximal lordotic correction from an anterior-only approach.

54.9 Difficulties Encountered

The bifurcation of the great vessels usually occurs around the L4/5 disk space. To expose the L4/5 disk the common iliac vein needs to be retracted to the right, placing the iliolumbar vein at risk of avulsion. This injury is difficult to control because the vascular injury is usually deep to the left common iliac vein. Many surgeons prefer to routinely ligate the iliolumbar vein when operating at L4/5 to avoid this risk. Double clipping and coagulation starting a few millimeters from the parent vessel seems to be reasonably safe. Some prefer ligation or transfixation and ligation.

54.10 Key Procedural Steps

The initial technical steps in positioning and approach are the same as for other anterior lumbar interbody procedures. Several variations are described. We describe the senior authors' preferred approach technique for L4/5 and L5/S1.

A skin incision is made that is vertical below the umbilicus or transverse in the line of the disk space. Subcutaneous dissection identifies the fascia, which is well exposed for easier closure. This is divided longitudinally with scissors or electrocautery, about 1 cm to the side of the linea alba, allowing for easier closure. The rectus muscle is dissected from the midline and elevated. Branches from the epigastric vessels to the fat are coagulated and the remaining vessels are elevated with rectus muscle. The bright yellow fat of the retroperitoneum is swept medially with long swabs on sticks to demonstrate the psoas muscle. The peritoneum and the fat are retracted medially and the vasculature medial to psoas and anterior to the spine is visualized. At this stage, the vascular work needed to expose the disk is dictated by the level(s) of the operation and a patient's individual anatomy. L5/S1 is always approached between the iliac vessels and the median sacral vessels are then sacrificed. Bipolar coagulation is preferred to unipolar to minimize risk of damage to the inferior hypogastric plexus.

Usually, to expose L4/5 and always to expose L3/4 and above, the posterior rectus sheath at the arcuate line needs to be divided vertically. This is most easily done laterally where it blends with the anterior sheath. At this position, the surgeon is less likely to enter the peritoneum. If the peritoneum is opened, it should be repaired promptly with 2/0 Vicryl to prevent propagation of the tear and bowel filling the retroperitoneal space.

The left iliolumbar vein below L4/5 or the segmental vessels at L3/4 may require division to mobilize the iliac vessels to the right and gain access to the respective disk.

Exposure of the disk requires some gentle sweeping of vessels from the disk. Being directly on the disk provides the best

plane to work in. Previous surgery or dense adhesions may make vessel mobilization hazardous; at times, the approach may need to be abandoned rather than risk a difficult-to-manage vascular injury.

Retractor blades may now be placed at the respective disk levels. At L5/S1 the retractors are positioned above the disk space elevating the common iliac veins up and around the disk space. At L4/5 the blades are used to retract the vessels inferiorly below the disk space also using a straight blade in the midline to protect and elevate the bifurcation away from the disk space.

Annulotomy, diskectomy, and end-plate preparation are done in the usual fashion to ensure the best possible interface for fusion.

The interbody implant trial device is used to determine adequate sizing for height, width, and depth. A single anteroposterior shot is useful to confirm midline and a lateral radiograph is used to confirm correct depth.

End plates are rasped and the chosen cage inserted after being packed with bone graft or a substitute of choice.

Some devices have fixed-angle screws determined by the trajectory of holes; some allow some variability; generally, a pilot hole is drilled or awled. The length for the screws will be decided from intraoperative and preoperative measurements of the vertebral bodies. Generally, the wider and longer the screw the better the fixation, but screws must not perforate the posterior cortex or adjacent endplates. Sound biomechanical fixation is usually achieved with screws 20 mm or longer.

The most taxing part of device insertion at the L5/S1 level is usually insertion of the L5 screws, as the angle of screw trajectory often is such that the drivers impinge on bladder fat. A wide, malleable retractor or angled retractor is useful to retract the bladder and create space, as needed.

After device placement, the wound is copiously irrigated with antibiotic-containing fluid to remove any disk fragments. Screws and pins are removed, slowly and carefully, checking each hole for bleeding and applying bone wax as needed

Having ensured hemostasis, the posterior fascia is closed using a running nonabsorbable suture. The more superficial fascia can be closed in a similar way. The subdermal layer is closed using 3.0 inverted interrupted sutures with intradermic 3–0 undyed Vicryl for the skin.

54.11 Bailout, Rescue, and Salvage Procedures

- Small tears in the iliac vessels are addressed with primary suture repair. Large vessel injury may necessitate the assistance of a vascular surgeon.
- If non-union occurs with a stand-alone cage with incorporated screws, first-choice treatment would be to add posterior pedicle screws and bone graft. Revision anterior surgery should be avoided unless absolutely necessary (i.e., infection).
- In cases of non-union where posterior screw supplementation is contemplated, it is important to review a CT scan to ascertain the feasibility of the screw placement to avoid the previously placed anterior screws. This has rarely been a problem.

Pitfalls

- Retrograde ejaculation is a highly feared complication that may occur with surgery on the lower anterior lumbar spine; the male patient should be made aware of this potential complication. It may be less with a right-to-left dissection at the L5/S1 level as the hypogastric plexus is mobilized with the peritoneum. Injury is reported to be more likely with the transperitoneal technique. Limiting coagulation of vessels is prudent.
- Postoperative ileus can occur. Patients should be allowed only fluids, confirming flatus or bowel sounds before advancing the diet.
- Postoperative X-rays should be obtained to confirm placement of the cage and to look for signs of subsidence with the patient standing prior to discharge. If end-plate injury occurs at surgery or early subsidence occurs, then posterior screws should be considered.
- Significant alteration in the hematocrit postoperatively, especially when the surgery was uneventful, should be investigated with a CT scan of the abdomen to evaluate for a possible retroperitoneal hematoma or hematoma from the inferior epigastric vessels.

55 Anterior and Anterolateral Lumbar Fixation Plating

Thomas N. Scioscia

55.1 Description

Recent advances in plating systems have made anterior fixation possible after anterior lumbar interbody placement. Following a supine retroperitoneal or transperitoneal approach, diskectomy is performed and end plates are prepared to bleeding bone. The anterior lumbar interbody fusion (ALIF) graft of choice is then press-fit into the interspace. Fixation is achieved with a low-profile conventional or locking plate. After meticulous hemostasis, abdominal closure is performed. Alternatively, a zero-profile device can also be used at all lumbar levels. Anterolateral plating is performed through a lateral retroperitoneal approach. After exposure and corpectomy, a structural graft or cage is placed to re-create lordosis. A low-profile conventional or locking contoured plate is then applied laterally with two screws in the superior and inferior vertebral bodies.

55.2 Key Principles

Fixation by the means of plating increases stability to a fusion construct. Cages alone have produced inadequate fusion rates. Anterior fixation decreases micromotion, which increases the fusion rate. A plate is more likely to be a stronger construct than a zero-profile device, but has limitations due to anterior vascular anatomy above L5–S1. The zero-profile device can be used at all levels in the lumbar spine, but has less stability and less room for bone graft. One must choose the right fixation for the appropriate patient by taking into account these principles.

55.3 Expectations

Fusion rates of stand-alone ALIF have been extensively studied, and pseudarthrosis rates of up to 35% have been reported. This may be due to the loss of the anterior longitudinal ligament, which increases instability in the flexion/extension plane. The advent of bone morphogenetic protein has also raised the concern of remodeling and weakening of femoral ring allografts. These problems have prompted surgeons to back up ALIF procedures with either standard or percutaneous pedicle screws. Anterior plates have been studied in vitro, and they restore the anterior tension band and sagittal stability. The risk of vascular injury tempered the early excitement about anterior lumbar plating, but newer designs have rekindled interest. The Pyramid plate (Medtronic) is specially shaped to fit below the bifurcation of the great vessels and has a cover plate to prevent screw backout (▶ Fig. 55.1). The anterior tension band (ATB) plate (Synthes Inc.) is a very low-profile plate (3.5 mm), and the screws lock into the plate, minimizing the risk of vascular erosion (▶ Fig. 55.2). These products are best indicated at L5–S1 as they are placed below the vascular bifurcation. At higher levels, zero-profile devices decrease the risk of vascular erosion and delayed vascular injury.

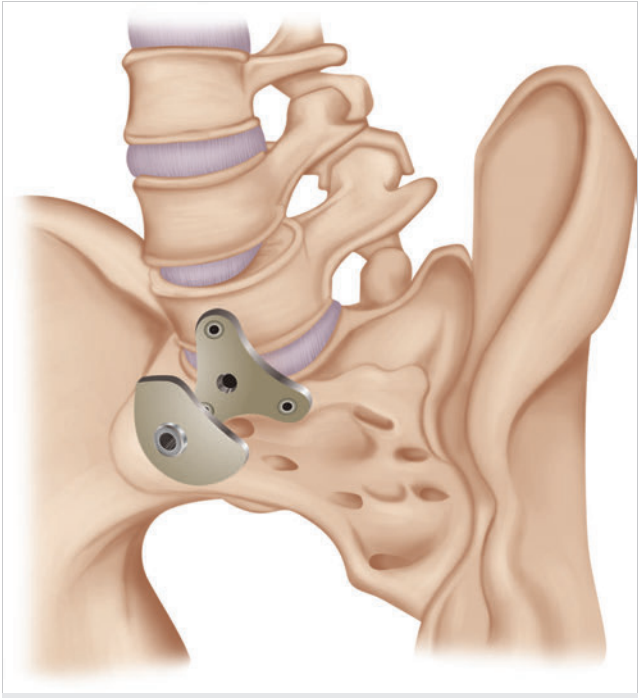

Fig. 55.1 Pyramid plate (Medtronic) placed at the L5–S1 interspace.

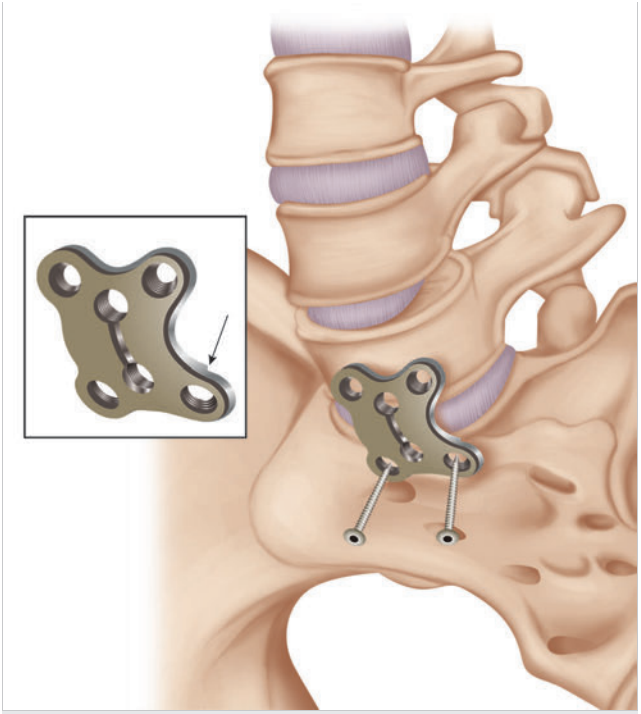

Fig. 55.2 The anterior tension band (ATB) plate (Synthes Inc.) placed at the L5–S1 interspace.

55.4 Indications

Indications are supplemental fixation after ALIF for diskogenic back pain with positive diskogram, instability, or grade I spondylolisthesis and pseudarthrosis after failed posterior surgery. The Pyramid plate is indicated only at the L5–S1 disk level. The ATB plate is indicated from L1–S1, although it should be placed anterolaterally above L5–S1 and used with extreme caution at these higher levels due to the potential for vascular erosion. A better option for the superior lumbar levels is the zero-profile device. The constructs with screws are generally indicated for spinal instability up to a grade I spondylolisthesis. The devices with blades or plates are indicated for degenerative conditions without instability due to less inherent fixation.

55.4.1 Relative Indications

Supplemental fixation after ALIF for revision of failed spine arthroplasty

55.5 Contraindications

- Instability with greater than 25% listhesis in any direction
- Any instability when utilizing a blade/plate zero profile device
- Low-lying bifurcation of the great vessels

55.5.1 Relative Contraindications

- Prior retroperitoneal surgery with adhesions
- Calcification of the aorta and iliac arteries
- Osteoporosis

55.6 Special Considerations

Great vessel anatomy must be visualized on magnetic resonance imaging (MRI). The bifurcation should be located superior to the L5 vertebral body when plating the L5–S1 interspace. If this is not the case, a zero-profile device should be used, or consent for posterior instrumentation should be obtained. Calcified great vessels visualized on preoperative radiographs should be retracted carefully to minimize the risk of a thrombotic event with catastrophic consequence. Pulse oximetry placed on the left second toe can alert the surgeon to the need for emergent thrombectomy of the left lower-extremity vessels. A retroperitoneal approach is favored over a transperitoneal approach. The transperitoneal approach is associated with a fivefold to 10-fold increase in retrograde ejaculation as a complication. Placement of the conventional Pyramid plate needs to be flush on both vertebral bodies because it relies on friction with the screw–plate–bone interface for fixation. This implies that all osteophytes must be removed and the plate may not be ideal with spondylolisthesis. The locking plate is a fixed-angle device that still affords stability even if the plate is not fully seated on bone. When placing the ATB plate at all levels above L5–S1, careful attention must be paid to the great vessels. When placing a zero-profile device, the largest device possible should be used. Maximum end-plate coverage by the cage itself will increase construct stability. Graft window area in some implants is compromised, which limits the amount of graft material that can be applied within the spacer.

55.7 Special Instructions, Positioning, and Anesthesia

All ALIF cases should be templated preoperatively to assess vascular structures and ease of access. Templating preoperatively will give the surgeon an accurate assessment of which construct to use. General anesthesia is mandatory and neuromonitoring is typically not needed. The patient is positioned supine and a lateral fluoroscopy view is used to mark the level of incision, which places the dissection parallel to the disk space before beginning the surgery.

55.8 Tips, Pearls, and Lessons Learned

An experienced access surgeon minimizes the risk of vascular injury during the approach. The placement of the interbody graft should be recessed a few millimeters in the disk space. Lateral fluoroscopy is helpful in identifying the disk space margins as the implant is seated and is useful to guide plate and screw placement. The osteophytes should be rongeured before plate placement to ensure maximum bony contact. The smallest plate possible should be used to minimize the risk of vascular erosion. Placement of the plate should be away from the vessels, avoiding direct placement under venous structures. Zero-profile implants should always be available to decrease the risk of aborting the procedure due to a low-lying vascular bifurcation.

55.9 Difficulties Encountered

During plating techniques, the most common difficulty is a low-lying bifurcation. This can be avoided by having a zero-profile device available. Another difficulty commonly encountered for all anterior fixation techniques is interference by the pelvis. A blade/plate construct does not rely on angling of screws and may be more helpful in this situation.

55.10 Key Procedural Steps

55.10.1 Direct Anterior Approach with the ATB Plate

A Pfannenstiel incision or a small left-side oblique incision is made, and the retroperitoneal approach is utilized to access the L5–S1 disk space. The middle sacral artery located in the midline is ligated. The diskectomy includes all of the nucleus, the cartilaginous end plates, the anterior anulus, and the anterior longitudinal ligament. Trial spacers are then impacted to a press-fit position. The implant is then packed with bone graft and is impacted into the disk space a few millimeters deep to the anterior vertebral body. The plates are sized using the smallest plate that will gain screw purchase into L5 and the sacral promontory. The L5–S1 plate has a cutout for the promontory, which is located on the inferior aspect of the plate. The

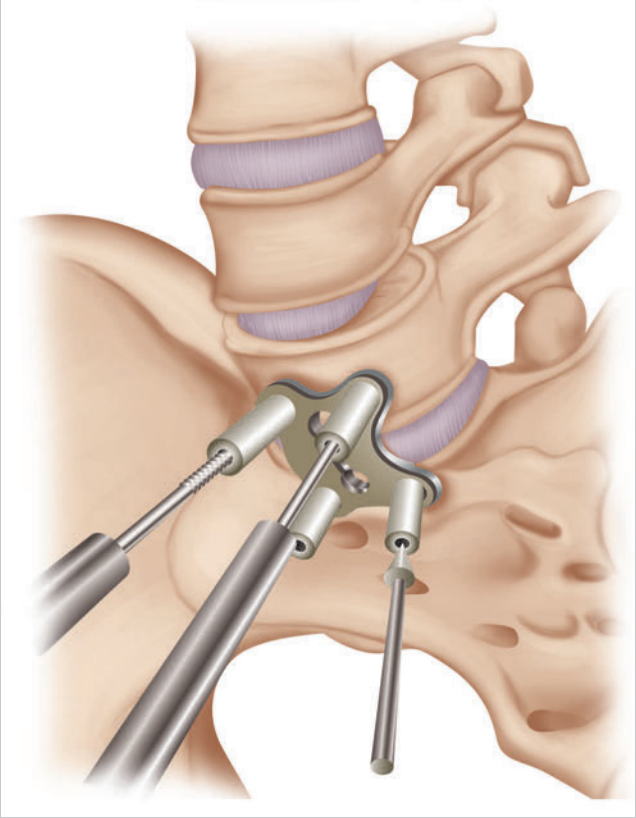

Fig. 55.3 The anterior tension band plate is provisionally fixed using the detachable fixation pins.

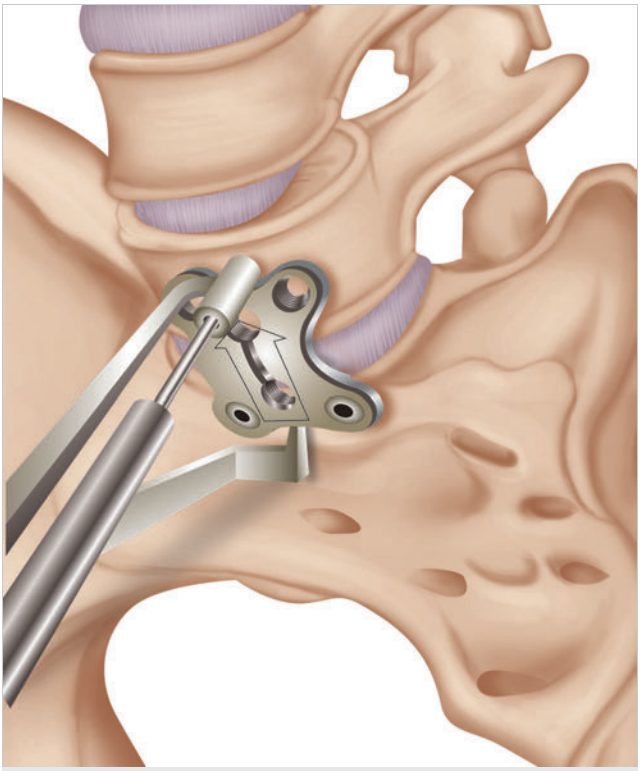

Fig. 55.4 The anterior tension band plate is compressed after placing the inferior locking screws.

correct-size plate is then placed on the interspace with all four threaded screw guides attached to the plate. Temporary fixation pins are placed in the contralateral screw holes, and fluoroscopy is used to confirm the correct plate position (▶ Fig. 55.3). The awl is used to prepare the remaining two screw holes through the threaded drill guide. The thread drill guides are removed, the depth gauge is then pushed through the cancellous bone, and the unicortical depth is measured. The screws are then placed and locked into the plate. The temporary pins are removed and the remaining screws are placed in a similar manner. For levels above L5–S1, the plate may need to be placed anterolaterally for better fit around the vessels. An alternative approach for compression may be performed by placing the two inferior screws first. A Schanz pin is placed in L5, and compression forceps are applied to the plate and the pin (▶ Fig. 55.4). The superior screws are then inserted in the previously described manner.

55.10.2 Anterior Approach Using the Pyramid Plate

Using the same surgical exposure, the interbody graft is placed in the L5–S1 interspace. The plate is placed with the narrow end over L5. The correct-size plate is then attached to the plate holder and placed in the proper position. The corresponding drill guide is then fastened to the plate using the screw-in mechanism. The awl is used to create pilot holes for screw placement. The correctly measured screws are placed through the guide into the plate. The guide is then disengaged from the plate and removed from the wound. The corresponding cover plate and holder are then introduced, and the post in the cover is fitted into the inferior opening of the Pyramid plate. The *T*-handle of the holder is then rotated clockwise seating the cover plate onto the Pyramid plate (▶ Fig. 55.5).

55.10.3 Anterolateral Approach with the Locking Thoracolumbar Spine Locking Plate (TSLP)

The left-sided approach is favored due to the position of the liver. The patient is placed in the lateral position, and a flank incision is made through the abdominal muscles. The peritoneum is reflected anteriorly, exposing the psoas muscle. The psoas muscle is dissected off the vertebral body to access the vertebral body for a corpectomy. An abdominal retractor set is utilized for complete exposure from the 12th rib to the iliac crest. After corpectomy, diskectomy, and placement of a cage or structural allograft, the plate is then trialed similar to the anterior ATB plating technique. The rest of the technique is identical to that for the ATB technique, with the exception that the plate is of different configuration and placed laterally. After application, a screw can be placed in the center hole through a structural allograft if desired (▶ Fig. 55.6).

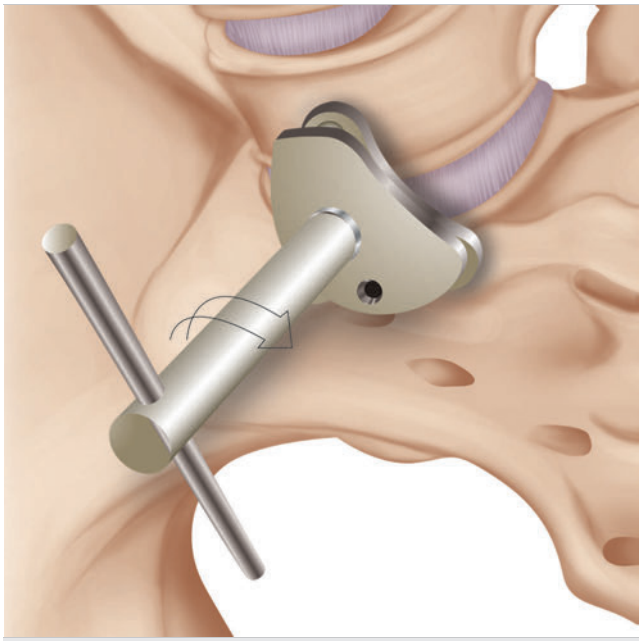

Fig. 55.5 The T-handle of the holder is then rotated clockwise seating the cover plate onto the Pyramid plate.

55.11 Bailout, Rescue, and Salvage Procedures

Percutaneous or conventional pedicle screws can be used if the plate cannot be safely placed. Posterior fusion can also be added for pseudarthrosis or fracture of the L5 vertebral body. Bed rest combined with a thigh extension thoracolumbar spinal orthosis (TLSO) may also be reasonable for vertebral body fracture until healing occurs. Pulse oximetry can alert the surgeon to lower extremity thrombosis and the need for emergent thrombectomy. Direct repair of the great vessels and the consideration for anticoagulation is the treatment of choice for great vessel injury.

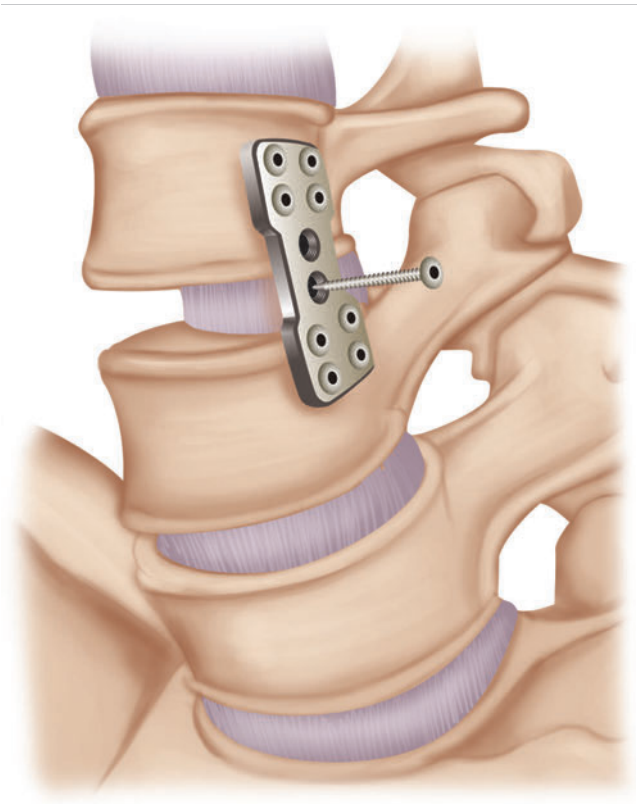

Fig. 55.6 The thoracolumbar spine locking plate is placed laterally and fixed with optional bone graft screw.

Pitfalls

- The biggest pitfall of the procedure is symptomatic pseudarthrosis.
- Great vessel injury can be catastrophic either during the approach or because of chronic venous erosion.
- Screw back-out causing injury is minimized by the locking technology and the low profile of the plate.
- Thrombosis in the left lower extremity is also a concern.
- Retrograde ejaculation and sterility is possible, especially when the transperitoneal approach is utilized.
- Hernia and bowel injury have also been reported.
- Sympathetic injury could cause unilateral leg symptoms.

Section XIII

Deformity

XII

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56 Understanding Spinal Alignment and Assessing Pelvic Measurement Parameters for Deformity Correction

Christopher M. Maulucci and Joshua E. Heller

56.1 Description

A complete radiographic evaluation of a spinal deformity in three dimensions is necessary before proceeding with surgery. The relationship of the pelvis to the spine is important in making clinical decisions.

56.2 Key Principles

Fixed anatomical parameters of the pelvis are the foundation upon which the degree of spinal curvature is based. Radiographs of the entire spine and pelvis should be obtained to evaluate the global balance of the spine in both the coronal and sagittal planes. Clinical outcomes studies have demonstrated that maintenance of sagittal balance, rather than coronal balance, results in greater clinical improvement.

56.3 Expectations

Through a thorough radiographic examination of the deformity patient, the most efficacious and safe surgical procedure can be planned.

56.4 Indications

Indications for operative intervention for a patient with a spinal deformity include

- Worsening pain
- Worsening neurologic function
- Radiographic progression of the deformity
- Failure of nonoperative management

56.5 Contraindications

There are no absolute contraindications to performing a deformity-correction surgery. However, multiple relative contraindications exist:

- Multiple medical comorbidities, especially cardiac and pulmonary—deformity procedures may be time consuming and result in significant blood loss
- Osteopenia or osteoporosis—poor bone health may result in hardware failure and pseudarthrosis
- Tobacco use leads to higher rates of pseudarthrosis and need for revision surgery.

56.6 Special Considerations

Conventional radiographs of the entire spine in anteroposterior (AP) and lateral projections must be obtained with the patient in a standing position with the hips and knees fully extended. This posture prevents the patient from employing compensatory measures such as hip and knee flexion to combat a kyphotic deformity that directs gaze downwardly. If the entire spine cannot be obtained on a single image, C7 marks the minimal cranial limit. The caudal limit of the image must incorporate both femoral heads.

When viewing the images, a standard convention applies. Anteroposterior radiographs should be seen with the right side of the patient on the viewer's right side. This orientation re-creates the view the surgeon has of the patient during gross observation of the spine posteriorly as well as during prone positioning in the operating room. Lateral radiographs are viewed with the patient facing right.

A number of measurements based upon these images should then be obtained. On the lateral radiographs, the proximal thoracic (T2–T5), main thoracic (T5–12), thoracolumbar (T10–L2), and lumbar (T12–S1) curves can be measured by the Cobb method. The lateral images can be used to measure pelvic parameters as well:

- Pelvic tilt (PT)—Angle determined by a vertical reference line from the center of the femoral heads and a line from the center of the femoral head to the midpoint of the sacral end plate (▶ Fig. 56.1a). This measures the degree of pelvic retroversion that may be used to compensate for sagittal imbalance.
- Sacral slope (SS)—Angle subtended by a line parallel to the sacral end plate and a horizontal reference line (▶ Fig. 56.1b).
- Pelvic incidence (PI)—Angle between a line perpendicular to the sacral end plate at its midpoint, and a line from the center of the femoral head to the sacral end plate midpoint. This is a fixed anatomical parameter, unlike pelvic tilt and sacral slope, which may change with positioning.

The sagittal vertical axis (SVA) can also be measured on the lateral radiograph (▶ Fig. 56.2). The SVA is measured as the distance between the posterosuperior corner of S1 and a plumbline from the center of the C7 body.

The AP images yield information such as the magnitude of scoliotic curves and coronal deformities. The degree of coronal imbalance (▶ Fig. 56.3) is measured as the distance between the C7 plumbline and the central sacral vertical line (CSVL), which is drawn through the center of the sacrum perpendicular to the floor.

By convention, kyphotic Cobb angles and SVA are denoted as "+" and lordotic Cobb angles and SVA are denoted as "-." Regarding coronal Cobb angles and deformities, those to the right are denoted as "+," and those to the left are denoted as "-."

56.7 Special Instructions, Positioning, and Anesthesia

Patient positioning can be challenging for those with severe deformities. Proper padding of the chest, hips, and knees is necessary to stabilize the patient on the table. A conventional X-ray can be obtained before beginning to determine if the deformity has changed with positioning under anesthesia.

Fig. 56.1 **(a)** Lateral projection convention radiograph demonstrating the method of measuring pelvic tilt. **(b)** Lateral projection conventional radiograph demonstrating the method of sacral slope measurement.

The anesthesia team should be notified if motor evoked potentials will be monitored during the surgery. This will prevent the use of muscle-paralyzing agents during critical parts of the procedure.

If there is evidence of spinal cord compression or concern for spinal cord injury during surgery, an adequate perfusion pressure should be maintained.

56.8 Tips, Pearls, and Lessons Learned

Dynamic lateral views of the lumbar spine may be helpful in determining the degree of instability of a spondylolisthesis. Additional views can be helpful in determining the stiffness of a deformity:

- Supine lateral bending
- Bending over a bolster
- Fulcrum bending
- Push and traction

Advanced imaging may be needed to complete the workup of a deformity patient. Computed tomography (CT) can be useful in evaluating deformities with an axial component. Computed tomography also provides detailed information of the bony anatomy, which may help in surgical planning. Magnetic resonance imaging (MRI) or CT myelography should be obtained for patients with neurologic deficits to locate the regions responsible for dysfunction. Computed tomography angiography or MR angiography can be obtained to evaluate the nearby vascular anatomy, which may need to be accessed for deformity correction.

A normal SVA is ± 0.5 cm.

As pelvic tilt increases, so does patient disability and pain. A PT greater than 20 degrees is considered abnormal and an indication that a patient is attempting to compensate for sagittal imbalance.

The ideal relationship between lumbar lordosis (LL) and pelvic incidence is represented by the equation: LL = PI ± 9 degrees. Therefore, when correcting a kyphotic deformity, the amount of LL created should be within 9 degrees of the pelvic incidence.

56.9 Difficulties Encountered

- Severely spondylotic patients may require extensive bony removal to achieve adequate correction. Preoperative planning with CT will be helpful.
- Contouring the rod to incorporate pelvic instrumentation may require the use of offset connectors.
- Focal regions of significant deformity correction (i.e., osteotomies) are most prone to pseudarthrosis. Careful selection of rod material and bone-void fillers in this region will help reduce this risk. There may be benefit to utilizing three- or four-rod constructs in patients undergoing pedicle subtraction osteotomy (PSO).

56.10 Key Procedural Steps

Long-segment constructs extending to the lumbosacral junction require more than posterior-only instrumentation terminating at the sacrum. This is a region prone to pseudarthrosis, especially in patients with a high pelvic incidence. Supplementation with a L5–S1 interbody fusion is often recommended. Extension of the construct to the pelvis may be needed for patients with poor bone quality, high pelvic incidence, or prior pseudarthrosis.

Osteotomies can produce significant deformity correction. A combination of techniques may be utilized to create global spinal balance. During severe deformity correction, temporary rod placement may be necessary as osteotomies, such as a pedicle subtraction osteotomy, can destabilize the spine and result in translation at the destabilized segment.

Fig. 56.2 Lateral projection convention radiograph demonstrating evidence of ideal sagittal vertical axis. The C7 plumb line intersects the posterosuperior aspect of the S1 end plate.

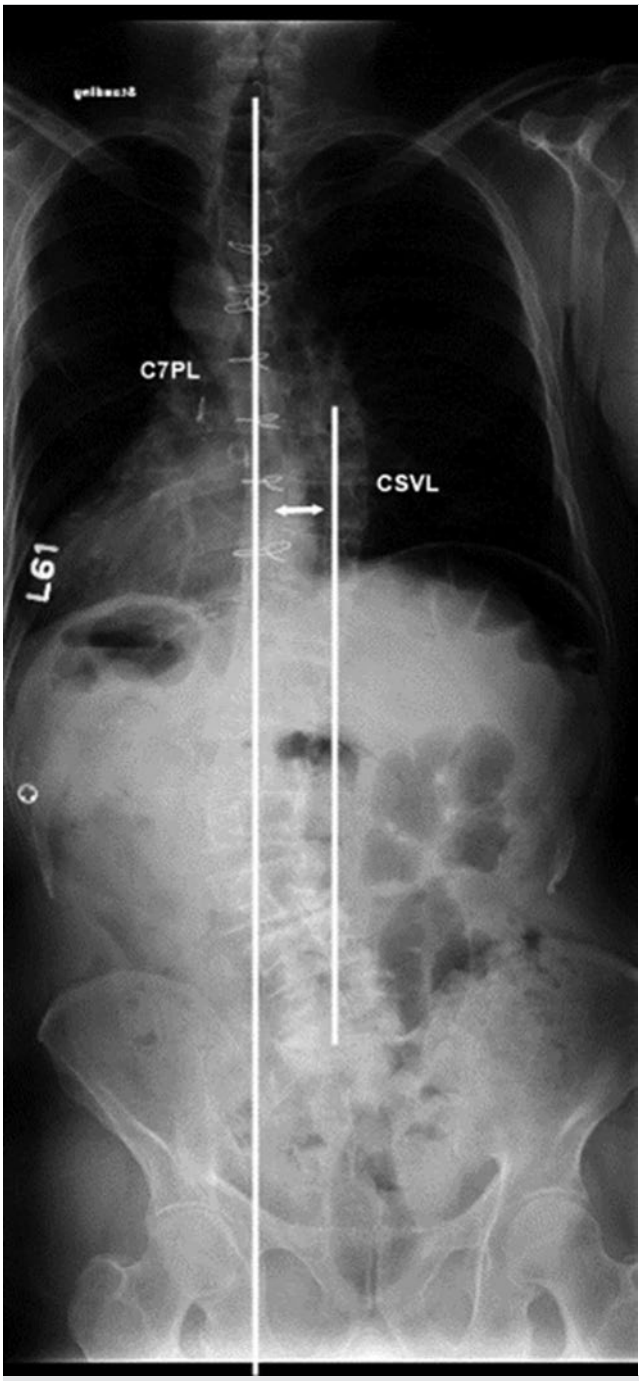

Fig. 56.3 Posteroanterior projection conventional radiograph with the C7 plumb line and central sacral vertical line identified. The distance between these two lines denotes the degree of coronal imbalance. By convention, levoscoliotic curves are given negative values, and dextroscoliotic curves, positive.

56.11 Bailout, Rescue, and Salvage Procedures

- If poor bone quality or anatomical variance, as assessed by CT, prevents insertion of pedicle screws, laminar hooks, or wires may be used to enhance spinal stability.
- Regions of instability may be reinforced with double-rod constructs.

Pitfalls

- Incomplete imaging of the deformity patient may result in an inadequate procedure that does not fully address a patient's symptoms. Without knowledge of the global spinal alignment and the spine's relation to the pelvis, proper deformity correction with lasting results may be difficult to achieve.

57 Patient Positioning for Cervical, Thoracic, and Lumbar Deformity Surgery

Niobra M. Peterson, Christopher Kong, Alexander R. Vaccaro, and Caleb Behrend

57.1 Description

Patient positioning techniques for maximizing visualization, access, and safety during spine surgery are described.

57.2 Key Principles

Optimal patient positioning relies on a thorough understanding of the procedural steps, inventory of equipment available, and variations in standard positioning techniques. The surgeon must also remain cognizant of instability, neurologic status, and hemodynamic lability when transferring or positioning a patient. Vulnerable areas such as bony prominences, eyes, and line insertion sites need to be checked vigilantly before committing to draping. Intraoperative imaging and the need for monitoring may also play a role in positioning of the arms and drapes.

57.3 Expectations

With appropriate positioning technique, the spine surgeon should be able to conduct surgery efficiently while minimizing risk of morbidity to the patient.

57.4 Indications

Patients can be positioned supine, prone, lateral, or sitting. Although the prone position is indicated for posterior approaches, anterior approaches can be performed via supine, lateral, or sitting positions, depending on the level and procedure. The indicated approach is chosen based on the location of compressive pathology, anatomical location of pathology, presence of instability, and patient-specific anatomy. Certain positions may increase the risk of particular morbidities such as pulmonary issues in the prone position in a patient with bilateral chest tubes.

57.5 Contraindications

Patient positioning may pose a challenge to monitoring, access, and hemodynamic support for the patient under anesthesia. In some cases, lines, leads, or ventilatory tubing must be temporarily disrupted or disconnected during positioning. This creates an opportunity for unobserved patient decompensation. Regardless of the patient's clinical stability or comorbid injuries, this juncture should be carefully coordinated with anesthesia.

A patient's variations in anatomy may preclude access with conventional patient positioning. Low aortic bifurcation and abdominal scar tissue are frequently cited contraindications to the anterior approach to the lumbar spine. Laryngeal nerve palsy usually contraindicates an anterior cervical exposure through the contralateral side.

Anesthetic concerns such as hemodynamic or respiratory instability are sometimes severe enough to render prone or sitting positions or even general anesthesia unfeasible. Inadequate equipment or untrained staff can also create an unsafe environment in which surgery should be temporarily delayed.

Some positioning-related complications may be noted on neurologic monitoring: for example, brachial plexus injury or vascular ischemia following taping of the shoulders.

57.6 Special Considerations

When selecting a table for the procedure, ensure that the room size is adequate to accommodate not only the table, but the microscope if needed, cell saver, and fluoroscopy equipment as indicated. Among the many tables and frames to choose from, the radiolucent table remains quite versatile. It can be used for anterior lumbar and thoracic approaches as well as cervical approaches. The Andrews frame allows for prone positioning with added hip flexion to improve access to the lumbar intervertebral disk spaces. The Jackson frame can be used for prone, supine and lateral approaches, but it is particularly useful for its ability to flip the patient intraoperatively while keeping them secured into the frame. After selecting the appropriate operative table, bumps, bolsters, sheets, tape, and deflatable bean bags can be used to fine-tune and secure additional positioning adjustments. To keep the arms from obstructing surgical access and fluoroscopic imaging, they can be strapped to arm boards or kept at the patient's sides using sheet wraps, tape, sleds, or belts.

57.7 Special Instructions, Positioning, and Anesthesia

When prone, the abdomen should hang freely. This reduces venous pressure and can help decrease intraoperative blood loss. Arms should be positioned at less than 90 degrees of flexion with proper support of the shoulders and padding for the ulnar nerves, bony prominences, and cutaneous sensory nerves. When in the lateral position, placing the operative level over the break in the table allows for improved disk-space widening as the table is flexed. This technique can be reversed in deformity cases where the patient is placed with their concave side down and centered over the break in the table. Following the osteotomy, the deformity is reduced by bringing the table from the flexed position to horizontal.

Bumps or pads can be used to improve access when placed in areas such as under the sacrum when approaching L5/S1 interspace for an anterior lumbar interbody fusion, or between the shoulders for an anterior cervical diskectomy and fusion at lower subaxial levels.

The positioning of monitoring wires on the bed should accommodate how imaging will be used as well as prevent

wires from being cut by equipment that clamps to the bed such as a retractor system.

In cases where risk of neurologic injury is present due to chronic conditions such a cervical myelopathy, or instability from trauma or infection, baseline motor-evoked potentials (MEPs) and somatosensory evoked potentials (SSEPs) should be established before the patient is transferred from the hospital bed to the operative table. Subsequent readings should be taken before and after each major repositioning or reduction procedure. Accidental electrical burns via short-circuiting can be avoided by preventing the crossing of cautery and neuromonitoring wires.

If cervical instability is present, awake intubation will often need to be performed. Intrathoracic approaches may require bilateral bronchial intubation to allow for selective lung deflation.

57.8 Tips, Pearls, and Lessons Learned

Before surgery, some positioning-related injuries can be prevented by establishing active cervical and shoulder range of motion. When operating on the cervical spine, turning the operating table so that the patient's feet are towards the anesthesia cart frees up space around the operative site. A bump or roll can be placed behind the scapulae to position the cervical spine into lordosis. Alternatively, lordosis can be "dialed-in" with a pressure infuser gradually inflated in place of the bump. Once inflated, to prevent position loss during the case, care should be taken to ensure that the stop-cock is positioned close to both the pump and the outflow line. During supine cervical procedures, prophylactic application of Gardner-Wells tongs can prevent dangerous inadvertent head movements, should anesthesia become too light. When instrumenting the posterior thoracic spine, pedicle cannulation in cranial and caudal trajectories can be assisted by use of the Trendelenburg and reverse-Trendelenburg positions. During anterior approaches to lumbar disks, the anterior intervertebral space can be widened by placing a bump behind the patient at the surgical level. The use of a clear plastic drape can assist visual assessment of sagittal alignment when performing thoracic or lumbar deformity correction.

57.9 Difficulties Encountered

Despite the many measures taken in preparation, it may become clear intraoperatively that exposure or access is inadequate. In this setting, it is helpful to have an unscrubbed assistant, knowledgeable in operating-room equipment, available to make adjustments without contaminating the operative field. Additionally, the table control unit can be draped in a sterile condom and used by the surgeon to fine-tune table positioning intraoperatively.

Head positioning can alter the blood flow in the vertebral and carotid arteries, leading to brainstem and cervical spine ischemia with potential for neurologic injury. Rotation of 0 to 45 degrees or less is typically safe and a 2 to 3 finger-breadths thyromental distance is recommended with regard to flexion. Extremes of flexion, extension, lateral flexion, or rotation should be avoided.

57.10 Key Procedural Steps

Prior to transferring the patient to the operating frame or table, ensure that all padding and bumps are at the appropriate level and height. Verify that the anesthesia team is comfortable with the positioning plan, especially in the context of the patient's hemodynamic and respiratory stability. If neuromonitoring is in use, obtain baseline values before transferring the patient. During the transfer, delegate specific team members to supporting the head and cervical spine, protecting the limbs, preventing the pulling of lines and leads, and securing the head position via locking the headrest or Mayfield clamp once transferred.

Ensure that all bony prominences are padded, with special attention to the forehead, chin, shoulders, anterior superior iliac spines, thighs, knees, and malleoli. As indicated, care should also be taken to avoid pressure on the eyes, nose, axilla, ulnar nerve, genitals, and common peroneal nerve. If prone, space should be allowed for expansion of both the chest and abdomen. Breasts should be padded evenly. From the foot of the operating table, one should be able to verify that the hips and shoulders are leveled. Creams, frictionless covers, or bandages should be used where necessary to prevent skin shearing. Sequential compression devices should be applied to the legs to prevent deep vein thromboses. Arms should be placed in a position compatible with the patient's preoperative range of motion to avoid postoperative shoulder pain. Shoulders should not be abducted beyond 90 degrees to avoid undue traction of the brachial plexus. Likewise, excess traction should be avoided when shoulders are directed caudally with taping. Wherever possible, the patient should be covered with warming blankets to prevent hypothermia.

Before draping, skin well beyond the planned incision site should be shaved and sterilized. If performing posterior lumbar surgery, a plastic adhesive drape should be placed transversely, just cephalad to the gluteal cleft to protect against stool contamination. If any drape has difficulty remaining flush up against the skin, its position can be secured using skin staples.

57.11 Bailout, Rescue, and Salvage Procedures

In the event of a dural tear, the Trendelenburg position can reduce local intradural pressure and thus minimize cerebrospinal fluid loss. In lumbar surgery, this position can also be useful for decreasing blood loss via reduction of epidural vein engorgement.

If the patient is positioned prone, an additional bed or table in the room is useful for rapid supine repositioning in the event of an anesthetic emergency.

Pitfalls

- It is important to remain mindful of the hazards and limitations of the equipment and positioning used. An Andrews frame, though useful for lumbar decompression surgery, should not be used during fusion procedures as lordosis is affected by the high degree of hip flexion. If continuous skeletal traction is forgotten about during major deformity correction, injury to the cord may occur following paraspinal muscle dissection. If the surgeon is unwilling to make the necessary fine adjustments to positioning, tolerance of inadequate fluoroscopic imaging can lead to catastrophic injury due to wayward instrumentation.
- Beds have variable weight limits and this should be kept in mind when considering possible patient positions for a given patient.
- Finally, the importance of bony and soft tissue protection cannot be overemphasized. Inadequate eye protection in the prone position can lead to blindness via ischemic optic neuropathy or central retinal artery occlusion. Failure to protect peripheral nerves can lead to false drops in intraoperative MEPs and SSEPs due to neurapraxias. Regardless of adequate padding, prolonged procedures in the prone position can lead to severe facial swelling for the patient and can make extubation challenging immediately after surgery.

58 Reduction of High-Grade Spondylolisthesis

Dexter Bateman, Caleb Behrend, Alexander R. Vaccaro, Charles C. Edwards, and Charles C. Edwards II

58.1 Description

Full correction of high-grade spondylolisthesis is achieved through an entirely posterior approach, with or without sacral dome osteotomy, by using graduated instrumented distraction, posterior translation of the proximal spine, and flexion of the sacrum.

58.2 Key Principles

High-grade spondylolisthesis in L5 slips anteriorly and rotates inferiorly on the sacrum, producing a local kyphotic deformity. This sagittal imbalance produces compensatory pelvic retroversion, facet joint hypertrophy, lumbar hyperlordosis, and an overall postural deformity. High-grade slips frequently require surgery due to progressive deformity, refractory pain, or neurologic impairment. Gradual instrumented reduction is indicated for grade 4 spondylolisthesis and spondyloptosis. The sequential application of corrective forces through gradual instrumented reduction facilitates intraoperative stress relaxation. It can restore anatomical alignment with minimal morbidity with appropriate surgical planning.

58.3 Expectations

Careful preoperative planning, complete neural decompression, and gradual application of corrective forces over time with effective instrumentation consistently yield anatomical reduction of the spine. Anterior surgery is not necessary. Restoration of spinopelvic orientation reduces the potential for postoperative adjacent segment degeneration and slip progression, improves cosmesis and postural mechanics, and minimizes shear forces across the lumbosacral junction. Overall, reduction of high-grade spondylolisthesis improves the rate of a successful fusion. With precise execution, reduction may not increase the rate of iatrogenic neurologic injury as compared with arthrodesis in situ especially if an incomplete reduction (< 80%) is performed. For spondyloptosis, sacral dome osteotomy or additional stages of surgery may be necessary to limit nerve root stretch and prevent radiculopathy.

58.4 Indications

Reduction is indicated in high-grade spondylolisthesis and spondyloptosis for neurologic impairment, cosmetic dissatisfaction, and an increased likelihood of slip progression. Factors that influence slip progression include (1) slippage over 35% for children or 50% in adults; (2) female sex; (3) dysplastic changes of the L5 vertebral body (trapezoidal wedging) or the sacral end plate (doming); and (4) sagittal sacropelvic malalignment, including L5/S1 slip angle greater than 30 degrees and pelvic incidence greater than 70 degrees.

58.5 Contraindications

58.5.1 Lack of Patience or Surgical Experience

This is a technically difficult and demanding undertaking even for the most experienced spinal surgeon. The surgeon cannot force reduction ahead of stress-relaxation and nerve accommodation. Hands-on training, experience with lesser slips, and a long learning curve are necessary to master the planning and reduction techniques for consistently excellent results.

58.5.2 Older or Frail Patients

An aggressive surgery is rarely indicated in patients over 45 years of age.

58.6 Special Considerations

Preoperative planning is essential. Standing lateral and supine flexion/extension radiographs are needed to determine the "root-lengthening limit," which is used to avoid neurologic injury. First, make two tracings of the flexion lateral film: sacrum and L1–L5. To simulate complete reduction, the sacrum is flexed with its long axis oriented 35 degrees from the sagittal vertical axis. The L1–L5 tracing is then positioned with L5 reduced, L3 horizontal, and L1 vertically centered over the anterior body of S1 (▶ Fig. 58.1). To determine how much L5 nerve root lengthening will occur with full reduction, measure the distance from just below the L4 pedicle (root origin) to the sciatic notch (root exit) on the prereduction standing lateral and postreduction lateral tracings. The difference represents expected root lengthening.

The root-lengthening limit without deficit for one stage of surgery varies between 2 and 5 cm depending on several factors: (1) patient age greater than 20; (2) duration of ptosis exceeding 2 years; (3) L5/S1 slip angle greater than 50 degrees; (4) a stiff panlumbar lordosis demonstrated on bending films; or (5) prior lumbosacral fusion attempts. If all five predictors are present, only about 2 cm of lengthening is safe in one day, whereas if there are no negative predictors, 5 cm of lengthening is generally possible without deficit. If planned reduction exceeds the root-lengthening limit, there are two alternatives: (1) the reduction may be divided between two procedures a week apart; or (2) the spine is shortened by removing 0.5 to 1.5 cm from the proximal sacrum through a posterior sacral dome osteotomy.

58.7 Special Instructions, Positioning, and Anesthesia

Before surgery the patient practices ankle dorsiflexion for the wake-up test. An overhead traction frame is assembled over the

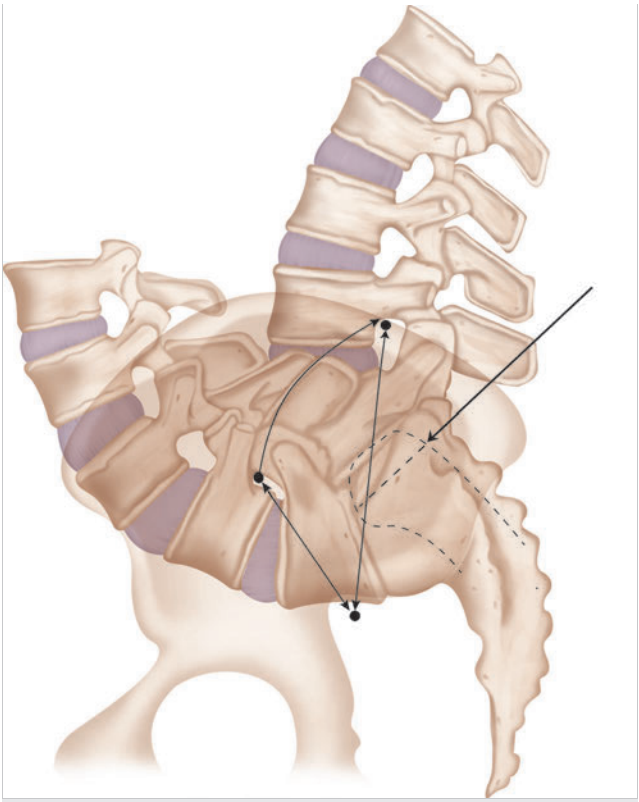

Fig. 58.1 Superimposed x-rays showing the starting and corrected positions of the lumbar spine on the sacrum, measurement of resulting nerve root lengthening and orientation of sacral osteotomy if needed.

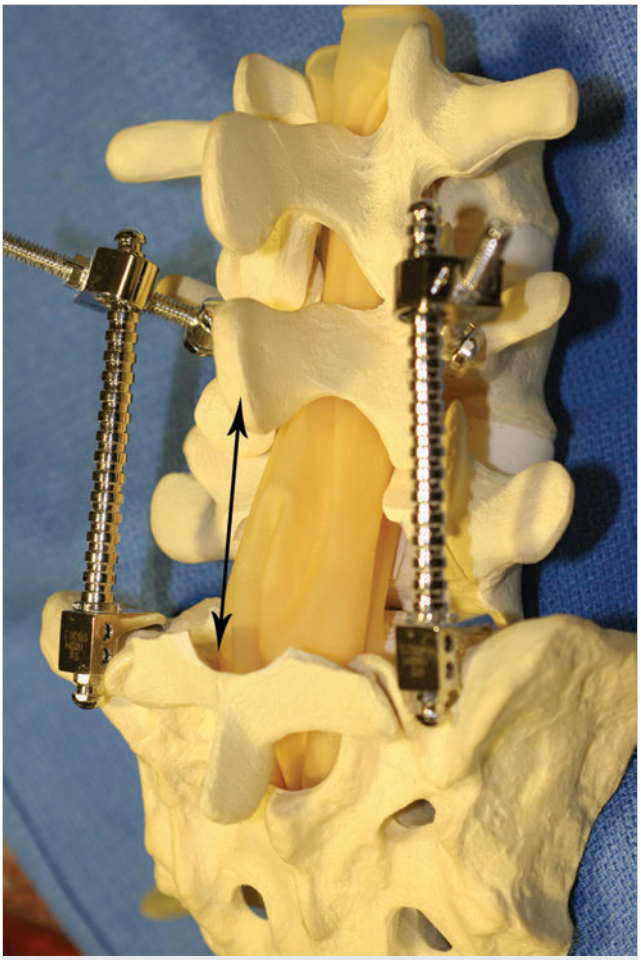

Fig. 58.2 Temporary alar rods permit distraction between hooks in the sacral ala and the L4 pedicle screw/adjustable connectors to incrementally raise L5 out of the pelvis.

head of the table. The patient is positioned prone with hips initially flexed 30 degrees to enhance lumbosacral visualization and knees flexed 70 to 90 degrees to relax the sciatic nerve. Hips are extended later to facilitate reduction.

58.8 Tips, Pearls, and Lessons Learned

The spondylo construct of the Edwards Modular Spine System (EMSS; Scientific Spinal) is specifically designed to facilitate this operation. It allows the surgeon to move and stabilize the spine simultaneously with 6 degrees of freedom. Controlled incremental change in spine position is made possible with ratcheted rods and threaded connectors.

58.9 Difficulties Encountered

The relationship of L5 to the sacral ala and L5 transverse process changes during the reduction sequence. The L5 roots need to be checked often during reduction to ensure no compression is present. Reduction lengthens the L5 root, which must also be checked for excessive tightness in addition to somatosensory evoked potential (SSEP)/electromyogram (EMG) monitoring. Reduction must be stopped if there is depression of the SSEP or EMG response or excess nerve tightness to palpation. Additional sacral shortening, root decompression as it crosses the ala, or an additional stage may be needed to safely complete the reduction.

58.10 Key Procedural Steps

- Exposure: Expose the spine from L3 to S2 carefully, as spondylolisthesis patients have a higher rate of spina bifida occulta. Identify and protect the L3–L4 and L4–L5 facet capsules. L5 may sit anterior to the sacrum and be difficult to see. Partial reduction is therefore needed to safely decompress the L5 roots. This is accomplished with concurrent ala rod distraction and posterior traction.
- Ala rods: Insert EMSS Combination Connectors (reduction screws) into the L4 pedicles without injuring the facet capsules. Combination connectors consist of a pedicle screw–swivel joint–threaded rod and adjustable ring body. Next, insert the shoe of high (10 mm) anatomical hooks into holes burred in the top of each sacral ala. A short ratcheted universal rod (EMSS) is inserted into the hook distally and into the ring body of the L4 combination connector proximally. The ring bodies are then distracted on the “ala rods” in small gradation to gradually raise L5 out of the pelvis (▶ Fig. 58.2).

- Overhead traction: Initial reduction to achieve L5 visualization requires both distraction and posterior translation of the lumbar spine. The posterior vector is provided by 18-gauge wires attached to the ring bodies of the L4 connectors or proximal end of the alar rods. The two sterile wires are passed to the anesthesiologist who ties them to traction rope. The rope passes over a pulley attached to the trapeze erected over the head of the bed; 20 to 30 lbs are added to the end of each rope to create the cephalodorsal vector. Sequential distraction of the alar rods combined with the constant pull of dorsal traction yields stress-relaxation of the contracted anterior tissues. The L5 vertebra gradually rises out of the pelvis and around the sacral dome.
- L5 root decompression: Remove the L5 arch as a single block using the Gill technique. The L5 roots are covered by the medial edge of the superior facet of L5 and pars nonunion fibrocartilage. Use a Woodson and curette to define a safe margin and a Kerrison punch; begin the decompression just proximal to the L4–L5 facet joint. With care, resect redundant ligamentum flavum, the osteophytic medial projection from the L5 superior facet, and fibrocartilage covering the L5 roots. Continue to widen the decompression laterally across the iliolumbar ligaments until the L5 roots pass anterior to the sacral ala. To prevent root injury, the L5 root must be continuously checked to ensure that there is no compression or excessive traction during reduction.
- Sacral osteotomy: If the preoperative planning radiographs and root-lengthening limit calculations indicate the need for proximal sacral osteotomy, the L5 and S1 roots and dural sac are fully mobilized to expose the sacral dome. The epidural venous plexus overlying the anulus is cauterized with a bipolar electrode. A ¼-inch osteotome is tapped into the sacral dome and adjusted under C-arm visualization until it matches the position planned for the osteotomy on the preoperative radiograph (▶ Fig. 58.1). The osteotomy is completed with ½-inch osteotomes from one side and then the other side of the dura. The posterior anulus is then resected from its origin on the posteriorly projecting osteophyte at the base of the L5 vertebral body using curved osteotomes and a large pituitary rongeur. The resected sacral dome is cut into sections and removed in pieces together with the lumbosacral disk. If more than 1 cm is removed from the sacral dome, it is necessary to fashion posteromedial to anterolateral channels (pseudoforamen) into the superior ala for the L5 roots to exit between the L5 transverse processes and the sacral ala.
- The spondylo construct: Once ala rod distraction and posterior translation from overhead traction have raised L5 out of the pelvis, screws can be safely inserted into L5. With the L5 nerve root and medial pedicle cortex under direct view, the L5 pedicle is cannulated with a blunt probe. After confirmation of appropriate trajectory with biplanar C-arm views, combination connector (EMSS) screws are inserted into L5. S1 screws may be directed either medially through the sacral pedicle or laterally across the ala. Bicortical ala screws are preferable after generous sacral osteotomy. A second point of distal fixation is needed to effectively control sacral rotation and to provide an adequate lever-arm for sacral flexion and mechanically sound fixation. When sacral bone is weak or the patient is obese, iliac screws can provide even stronger distal fixation. Midsacral alar screws, however, require less dissection and do not span the SI joints. Midsacral screws enter just proximal to the S2 dorsal foramen and are directed 45 laterally to converge with the S1 screws. The tips of the midsacral screws should wedge between the anterior and lateral sacral cortices adjacent to the SI joint. A cross-lock connects the distal end of the spinal rods to block dorso-lateral screw migration that can lead to pull-out. (▶ Fig. 58.3).
- Reduction: The first phase of reduction is to raise L5 out of the pelvis. This is accomplished by the overhead traction and ala rods. Further correction is achieved by incrementally distracting and shorting the L5 connectors. First, shorten the connectors until resistance is felt, and then distract the connectors to separate the L5 body from the sacrum. Sequentially shorten (tighten) and distract (ratchet) the connectors to two-finger tightness every 5 to 10 minutes. Re-image to determine the relative amount of distraction versus translation required. Periodically check the L5 roots with a probe to ensure that they do not become overly taut or compressed between the L5 transverse process and the ala. Allow 30 to 60 minutes per grade for stress relaxation of the contracted anterior tissues to permit reduction of the deformity (▶ Fig. 58.3b). Reduction is continued until (1) alignment is satisfactory; (2) the root-lengthening threshold is met or nerves become excessively taut; or (3) nerve function deteriorates on intraoperative monitoring or wake-up testing. If intraoperative monitoring demonstrates changes concerning for nerve injury, the reduction should be gradually reversed.
- Optional stage 2: If a subsequent stage is required to safely complete the reduction, the instrumentation is locked in place, and the wound closed (▶ Fig. 58.4). Patients are kept on bed rest for 4-7 days. We usually begin the second-stage reduction with the patient awake. We have found that patients consistently experience sciatic pain from excess root stretch long before any change can be detected on EMG or SSEP. The surgeon is able to continuously monitor motor function by talking with the awake patient and observing ankle dorsiflexion. Once L5 is positioned on top of the sacrum within a few millimeters of anatomical alignment, the L5 connectors are compressed toward the sacrum to restore lordosis and further shortening until an acceptable alignment is achieved. Once reduction is nearly complete, the patient is given general anesthesia. The instrumentation is locked into its final position and any further needed root decompression is performed, followed by posterolateral decortication and iliac crest grafting (▶ Fig. 58.5).
- Postoperative bracing: Following surgery, our patients are routinely mobilized in a custom-made, below-the-breast thoracolumbar spinal orthosis with a thigh cuff extension. The brace provides for patient comfort and is thought to lessen biomechanical stresses on the fusion construct. Upon discharge, patients may ambulate in the brace, which is ultimately discontinued after 3 to 4 months.

Using this method of gradual posterior instrumented reduction, successful correction of high-grade deformities, primarily spondyloptosis, can be performed without the need for an anterior surgical approach.

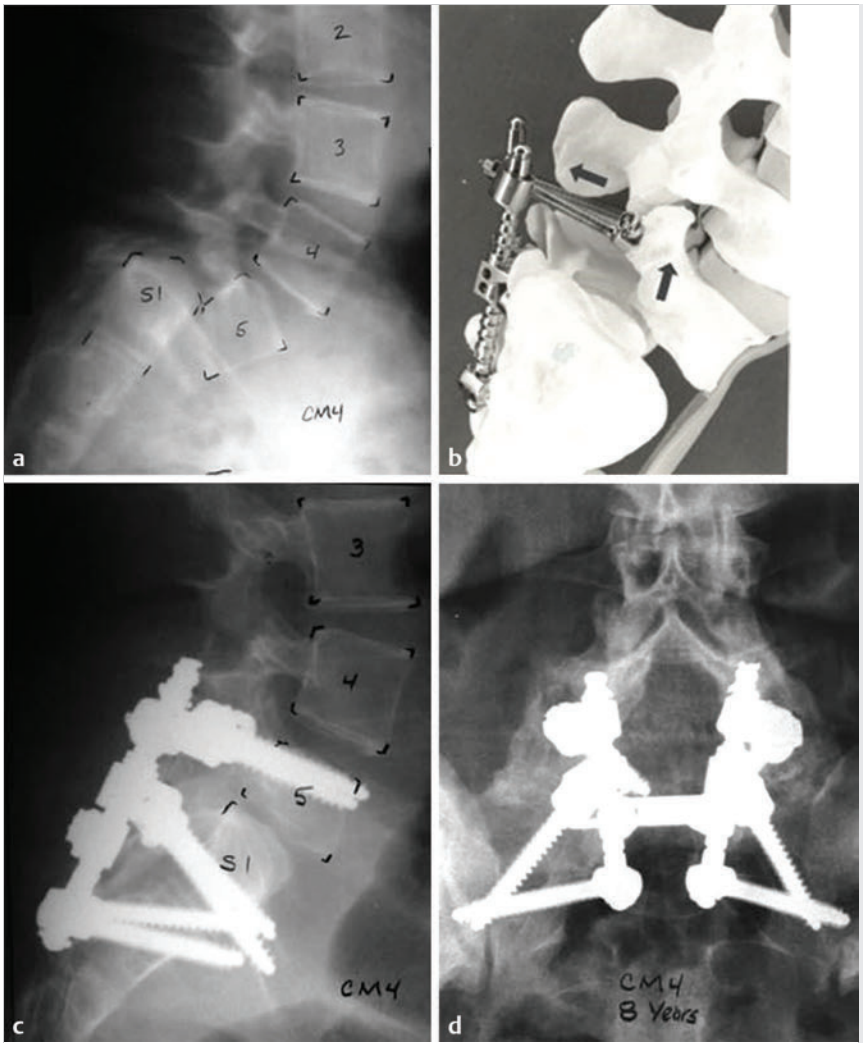

Fig. 58.3 (**a**) Pre-op radiograph of borderline spondyoptosis; (**b**) spondylo construct on model with adjustable connectors extended early in reduction sequence; (**c,d**) 8 years post-op radiographs to show the correct position of sacral screws and rod cross-lock.

58.11 Bailout, Rescue, and Salvage Procedures

- If radiculopathy occurs during or after surgery, reduction should be reversed until there is no root impingement, while still maintaining stable fixation. Following 1 week of bed rest, a subsequent reduction may be completed.
- If it is not possible to obtain secure bilateral pedicle screw fixation at L5, the instrumentation should be extended to L4.
- If deep infection develops, sequential debridement, open wound treatment, and appropriate intravenous antibiotics should be utilized until the infection resolves. However, the instrumentation should not be removed until fusion is solid.
- Although reduction is more challenging in adult spondyloptosis, adding an additional third stage to prevent excessive root stretch permits more gradual tissue relaxation. Rarely, progressive L4–L5 kyphosis develops after reduction of spondyloptosis in very young patients. If it is painful or seriously impairs sagittal alignment, the instrumented fusion may be extended to L4.

Pitfalls

- The most common pitfall is an attempt to rush the reduction and forgo the time necessary for relaxation of contracted anterior tissues. Accelerating reduction faster than the rate of nerve root accommodation, typically due to early overdistraction, causes radiculopathy. Careful preoperative planning, gradual instrumented reduction, and sequential staging for borderline cases can help to prevent neurologic injuries. Additionally, abrupt manipulations, application of excess force, and the distraction of L5 more than a few millimeters above the sacrum should be avoided.
- A second common pitfall is failure to adequately check and decompress the L5 roots at each stage of reduction.
- Lastly, a third pitfall is the insertion of an interbody spacer or graft between L5 and the sacrum. Insertion of a spacer undermines the rapid fusion achieved with direct apposition of the decorticated inferior end plate of L5 with the osteotomized body of S1. Furthermore, in high-grade spondylolisthesis the device induces additional distraction of L5 relative to the sacrum, increasing the degree of root-stretch and likelihood of radiculopathy.

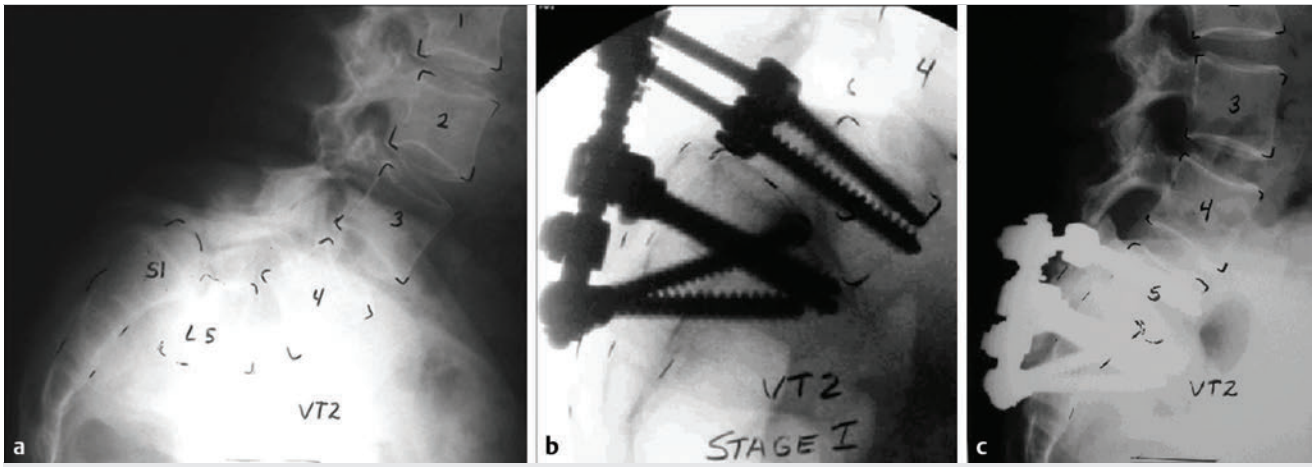

Fig. 58.4 (**a**) pre-op advanced spondyloptosis with location of planned sacral osteotomy; (**b**) partial reduction after first stage; (**c**) completed reduction 2 years post-op.

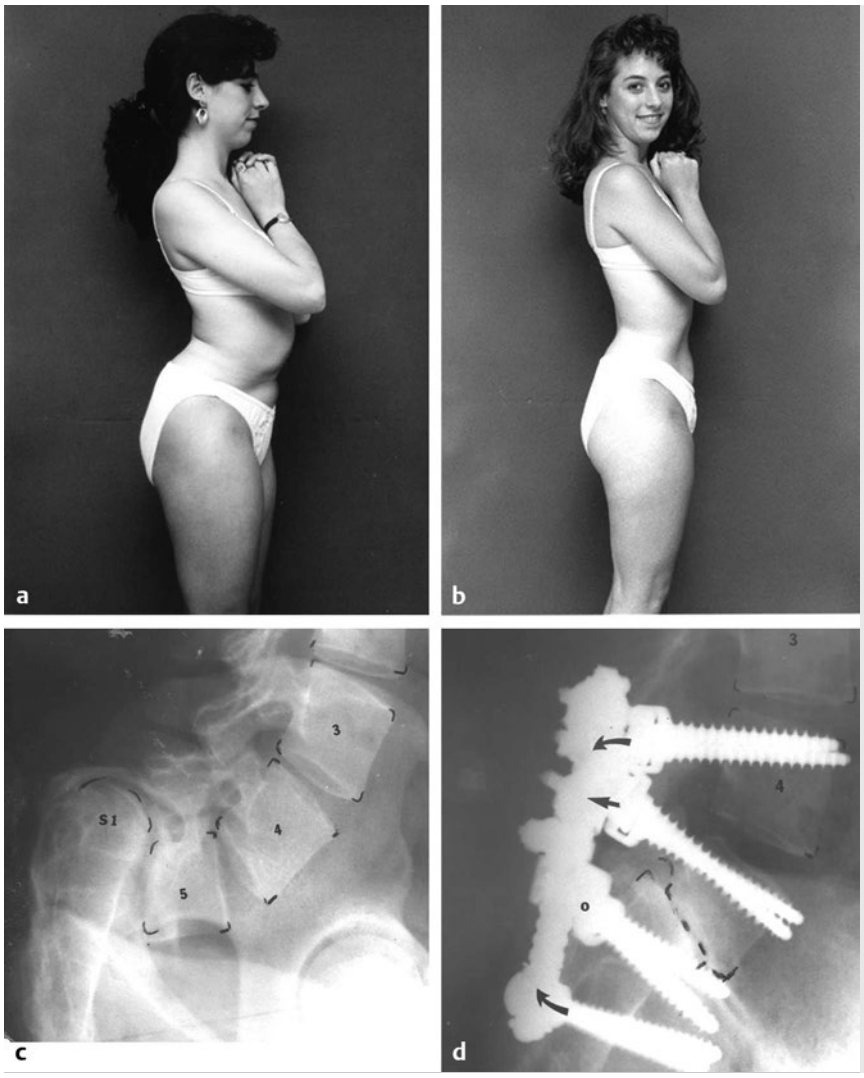

Fig. 58.5 (**a**) Pre-op photo showing foreshortened trunk and displaced thorax; (**b**) 2 year post-op photo after restoration of normal anatomy; (**c**) severe spondyloptosis pre-operative radiograph; (**d**) post-operative radiograph showing corrective forces after application of L4–S1 compression.

59 Gaines Procedure for Spondyloptosis

Tyson Garon, William A. Robinson, and C. Chambliss Harrod

59.1 Description

The Gaines procedure involves a complete L5 vertebrectomy for symptomatic spondyloptosis and is an advanced spinal deformity procedure involving staged or simultaneous anterior and posterior reconstruction of the lumbosacral junction. It is a technically demanding operation that necessitates a meticulous spinal imaging workup and physical evaluation along with the assistance of an access surgeon to perform safely and ensure optimal patient outcome.

59.2 Key Principles

Slippage of the vertebrae (spondylolisthesis) can occur via different etiologies (degenerative, isthmic, dysplastic, iatrogenic, traumatic) and has various classifications. Isthmic spondylolistheses with pars defects at the L5 vertebrae can be classified by Meyerding as low (< 50%) grade (I or II) or high grade (> 50%, III or IV). Spondylolisthesis progression is determined by vertical loading of the spinal column over the sacrum creating a shearing moment through the lumbosacral junction or disk space. When maximum compensatory hyperlordosis and paraspinal musculature fail, high-grade slips can progress to complete dislocation of the L5 vertebral body anterior, and subsequently, inferior to sacral promontory (▶ Fig. 59.1). Resection of the anterior then posterior portions of the L5 vertebral body with realignment of the L4 vertebrae onto the S1 vertebrae allows comprehensive correction of severe lumbosacral kyphotic deformity and posture with decompression of the neural elements. Stabilization with posterior instrumentation and arthrodesis of L4 to S1 affords long-term satisfactory alignment and prevention of deformity recurrence (▶ Fig. 59.2).

59.3 Expectations

The Gaines procedure is limited to the L5 vertebrae (or lowest lumbar vertebrae depending on transitional anatomy). A thorough history, physical exam, and review of radiographic images are essential (advanced imaging modalities including magnetic resonance imaging [MRI] and computed tomography [CT]) in understanding the exact locations of the great vessels, ureters, spatial location of the L5 vertebrae with respect to S1, the complete path of the L5 nerve roots, and posterior spinal elements. Detailed informed consent with emphasis on possible adverse complications and realistic expectations is an important aspect of the educational process for the patient and family. Blood loss, operative time, decision making for single day or staged reconstructions often vary based on intraoperative events and should be emphasized. Neurapraxias involving the L5 roots may occur with correction of the deformity.

59.4 Indications

Symptomatic spondyloptosis of L5 on S1 is the only indication for the Gaines procedure. Unilateral or bilateral lumbar radiculopathy and back pain often occur and persist despite efforts at conservative management. Lumbosacral kyphosis can be further disabling as compensatory pelvic retroversion and extension become limited and can increase difficulty of ambulation and the ability to stand upright with posterior musculature fatigue. Lesser degrees of lumbar spondylolistheses are better treated surgically with open or minimally invasive posterior, anterior, or combined reconstructive procedures with or without a direct neural decompression.

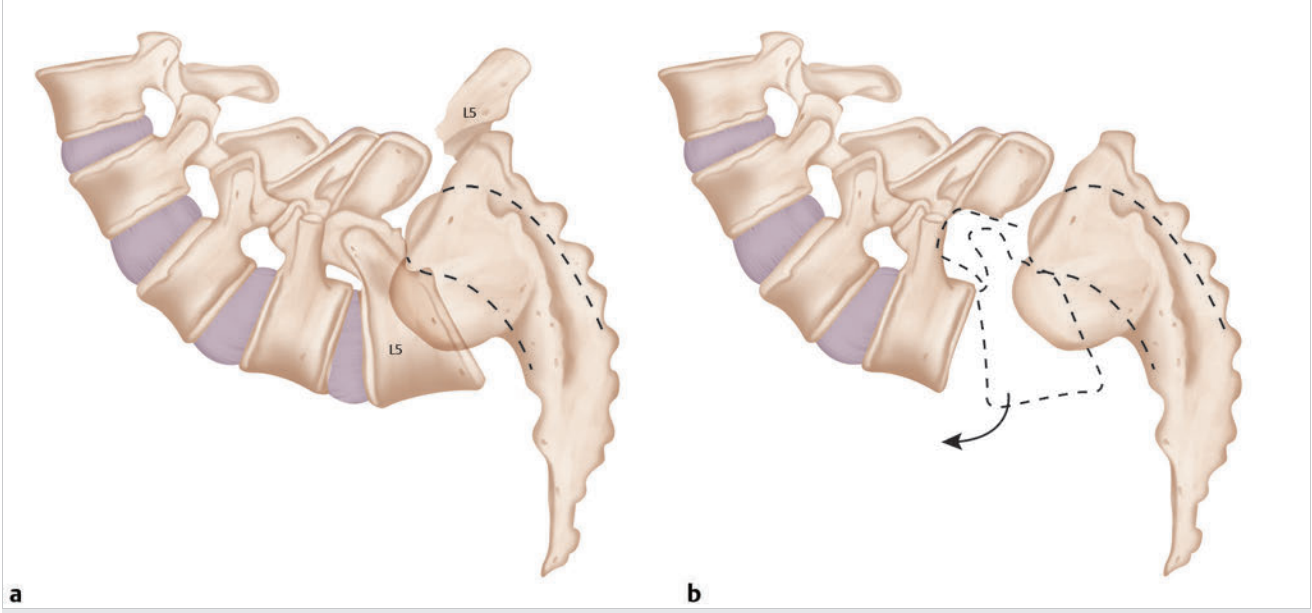

Fig. 59.1 **(a)** First-stage Gaines procedure. **(b)** The L5 vertebra, L5–S1 disk, and L4–L5 disk are removed.

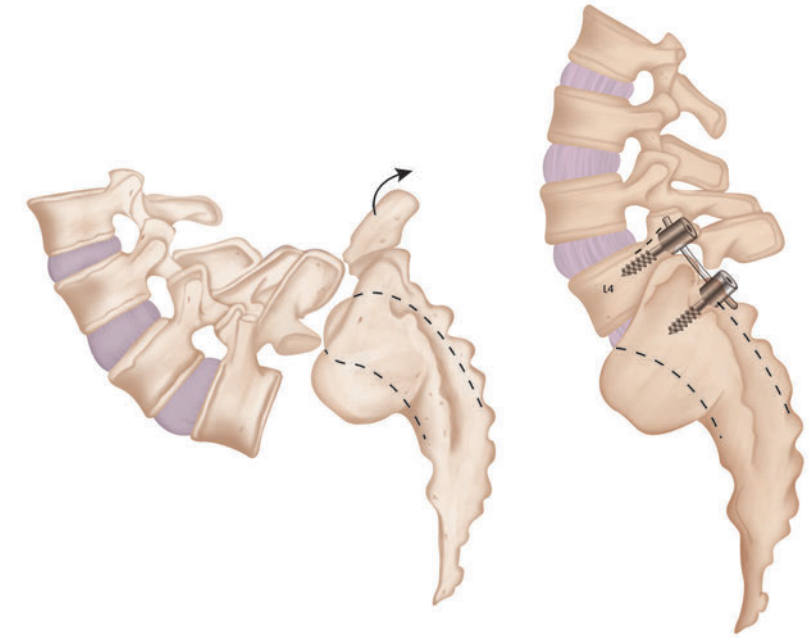

Fig. 59.2 Second-stage Gaines procedure. The lamina and pedicles of L5 **(a)** are removed to complete the L5 vertebrectomy, and the L4 vertebra (**b**) is placed on top of the sacrum and held in place with pedicular fixation.

59.5 Contraindications

Patients without lumbosacral spondyloptosis are contraindicated for the Gaines procedure. Patients too medically ill, those with anomalies of great vessels, severe retroperitoneal scarring, prior spinal infections in the area of surgery, or osteoporosis should be treated with other surgical techniques or nonoperatively with acceptance of the potential for progressive spinal complaints. Relative contraindications include lack of an experienced access surgeon or spinal surgeon, inadequate hospital support including anesthesia, intensive care, and neuromonitoring services. Only experienced deformity surgeons should engage in this procedure with comfort in all spondylolistheses management techniques. Patients refusing allogeneic blood products (e.g., Jehovah's Witness patients) may also be relatively contraindicated for this procedure.

59.6 Special Considerations

Careful initial preoperative radiographic evaluation cannot be overemphasized. Anteroposterior, standing lateral (flexion, neutral, and extension), lumbosacral spot views, and full-length 3-foot lateral and posteroanterior views are essential in understanding global spinal alignment, any deformity motion or reducibility, possible auto fusion of the anterior lumbosacral spinal margins, focal lumbosacral kyphosis, sacral promontory rounding, and local pelvic parameters (pelvic incidence, sacral slope, pelvic tilt, slip angle). Alternative procedures may be considered based on the above factors. Magnetic resonance imaging is invaluable for fully evaluating neural compression, possible dural ectasia, or spina bifida; CT is excellent at visualizing bony anatomy including planning for decompression, the placement of instrumentation, the location of planned osteotomies, evaluating bone stock size and density, and identifying the location of great vessels and presacral anatomy. Dual-energy X-ray absorptiometry (DXA) scans are helpful in diagnosing osteopenia and osteoporosis. Preoperative treatment of metabolic disease with the guidance of an endocrinologist can markedly improve bone quality and possibly decrease the potential of instrumentation failure. A CT/myelogram is useful in evaluating bony and neural anatomy especially following prior spinal surgery (particularly when prior instrumentation may distort MR images) or when dural defects or presence of meningoceles need further evaluation. Morbidly obese patients, revision cases, multiply abdominally operated patients, and suboptimal bone quality create more challenging environments.

59.7 Special Instructions, Positioning, and Anesthesia

Same or separate day anterior and posterior procedures are best performed on a radiolucent Jackson table that allows adequate intraoperative imaging. Supine positioning for the anterior approach can be helpful with placement of a bump under the sacrum versus hyperextending the bed to further bring the lumbosacral junction into better position from its particularly deep position due to the spondyloptosis. Length of surgery, blood loss, and hemodynamic stability typically govern decision making for proceeding with immediate or delayed posterior surgery. The use of a closed-circuit blood circulator (e.g., cell saver) can be of particular help in Jehovah's Witness patients who may refuse allogeneic blood products if the family consents to its use.

59.8 Tips, Pearls, and Lessons Learned

As stated above, complete understanding of the deformity and anatomy must be appreciated on preoperative imaging.

Talented, experienced access surgeons are strongly recommended for this operation. Anterior exposure can be very difficult and the spinal deformity obscures the sacral promontory until later in the operation. Vertical incisions are recommended over transverse abdominal incisions. If uncertain of one's exact location, use of fluoroscopic or intraoperative CT guidance is recommended. Long-handled instruments including scalpels, pituitaries, Cobb elevators, rongeurs, retractors, and occasionally high-speed burs are needed to access the deformity. Fixed circular retractor rings that can hold multiple retractor blades can decrease the need for additional surgical assistants, though caudal retractors often must be moved around frequently during the anterior procedure to "drop" the surgeons' hand for adequate access. Increased lateral exposure of the anterior elements is needed compared to standard anterior lumbar interbody fusion procedures. Posterior exposure must proceed cautiously to avoid inadvertent durotomy or neural injury due to often subcutaneous posterior element location of the remaining L5 vertebrae. Careful placement of modern transpedicular instrumentation can allow fusion at only between the L4–S1 level. Fluoroscopy or direct palpation of pedicles following Gill fragment removal or decompression can aid in accurate screw placement. Extension to L3 or iliac fixation is recommended when fixation is inadequate.

59.9 Difficulties Encountered

Inadequate anterior exposure (transverse incision, inexperienced access surgeon, inadequate retractor system or instruments), aberrant great vessel anatomy (low-lying aortic or caval bifurcation), retroperitoneal scarring, or inadequate lateral exposure may not allow complete resection of the anterior L5 vertebrae. Avoidance of injury to the presacral hypogastric plexus is vital in younger males to prevent sexual dysfunction, retrograde ejaculation, or impotence. Avoidance of electrocautery is recommended. Lateral exposure can allow identification of the L5 nerve roots with subsequent L5 pedicle resections. Careful retractor placement avoids L5 root compression inadvertently. Incomplete resection can make posterior L5 resection and reduction of L4 on S1 more difficult (or block it altogether). Accurate screw placement is required.

59.10 Key Procedural Steps

59.10.1 Anterior Approach

After correct supine positioning with a sacral bump or table hyperextension on a regular or radiolucent table, the procedure is best performed through a vertical infraumbilical incision extending to the symphysis (a transverse anterior abdominal incision extended across both rectus abdominis muscles is less frequently utilized and extension is limited if needed). Subsequent exposure of the great vessels is performed via a left-sided retroperitoneal dissection and retraction of the abdominal contents with placement of retractors. Initial anterior spinal exposure is typically the L4 vertebral body or the L4–L5 disk space deep within the pelvis between the aortic and caval bifurcation (▶ Fig. 59.3a). The caval anatomy (split) is right-sided and

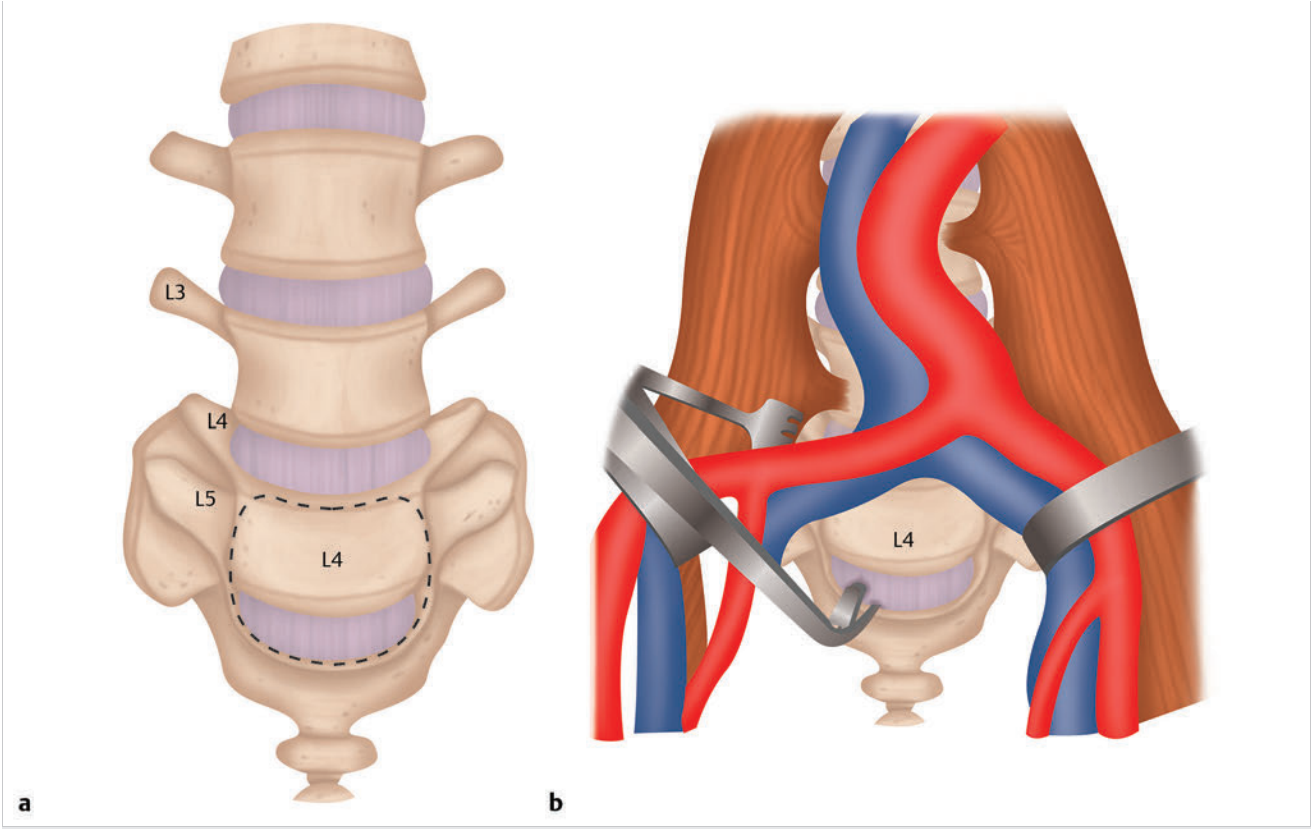

Fig. 59.3 (a, b) First stage. Anterior exposure for resection of the L4–L5 disk, L5 vertebral body, and L5–S1 disk.

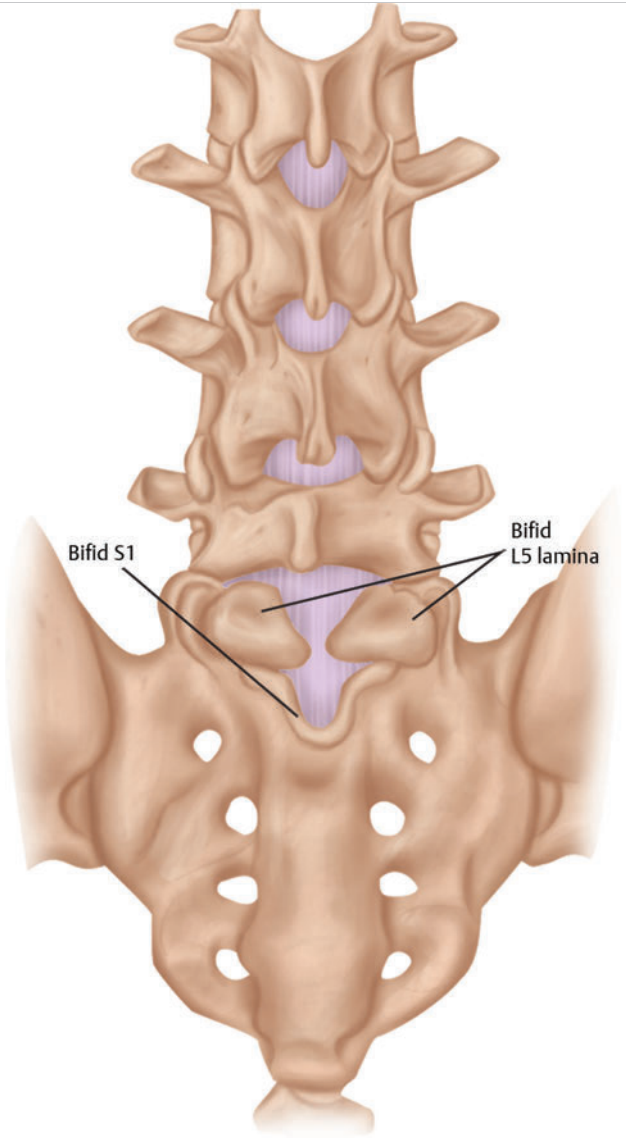

Fig. 59.4 Second stage. Posterior exposure from L2 to the sacrum. The L5 and S1 lamina frequently have a bifid structure.

typically more caudal and deep/posterior to the aortic bifurcation. The external and internal iliac vessels require mobilization to permit wide exposure of the L5 vertebral body with bilateral iliopsoas medial margin reflection yielding body–pedicle junction and L5 nerve identification. Exposure is now complete. After radiographic verification of the intended level is performed, the resection begins with a L4–L5 diskectomy. Often, removal of the anteroinferior L4 vertebral body is required initially. The inferior cartilaginous end plate of L4 is removed, but its cortical end plate is preserved. Resection of the L5 vertebral body is undertaken with varying osteotomes, rongeurs, and pituitaries until the base of the L5 pedicles bilaterally is found (▶ Fig. 59.3b). Lastly, a L5–S1 diskectomy is performed with preservation of the S1 superior cortical end plate. The abdomen is then closed.

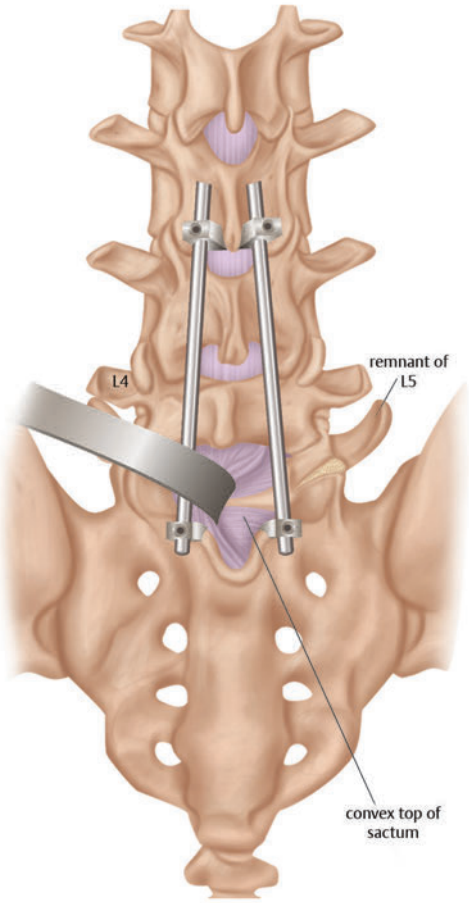

Fig. 59.5 Distraction between L2 and the sacral ala is achieved using hooks and rods. The posterior elements of L5 (pedicles, facets, transverse processes) are resected. The superior end plate of S1 and the inferior end plate of L4 are decorticated.

59.10.2 Posterior Approach

Exposure of the posterior spinal elements is done from L2 to the sacrum with care to avoid inadvertent durotomy or neural injury due to bifid spinous processes or laminae (▶ Fig. 59.4). Initially the L5 transverse process and pedicle are located beneath the sacral ala. Distraction is applied across the L4–S1 region to bring the L5 posterior elements including transverse process and pedicles into the surgical field. This is most commonly achieved using bilateral temporary rods between downgoing hooks placed into the sacral ala and upgoing hooks placed under the upper lumbar lamina (▶ Fig. 59.5). The L5 lamina, pedicles, facets, and transverse processes are carefully excised, while the L5 nerve roots are identified at all times. L4 pedicle screws are placed bilaterally with medially directed bi- or tricortical S1 screws placed with lateral fluoroscopy. Loosening and subsequent removal of the temporary rods permits reduction of L4 onto S1 by attaching the L4 and S1 pedicle

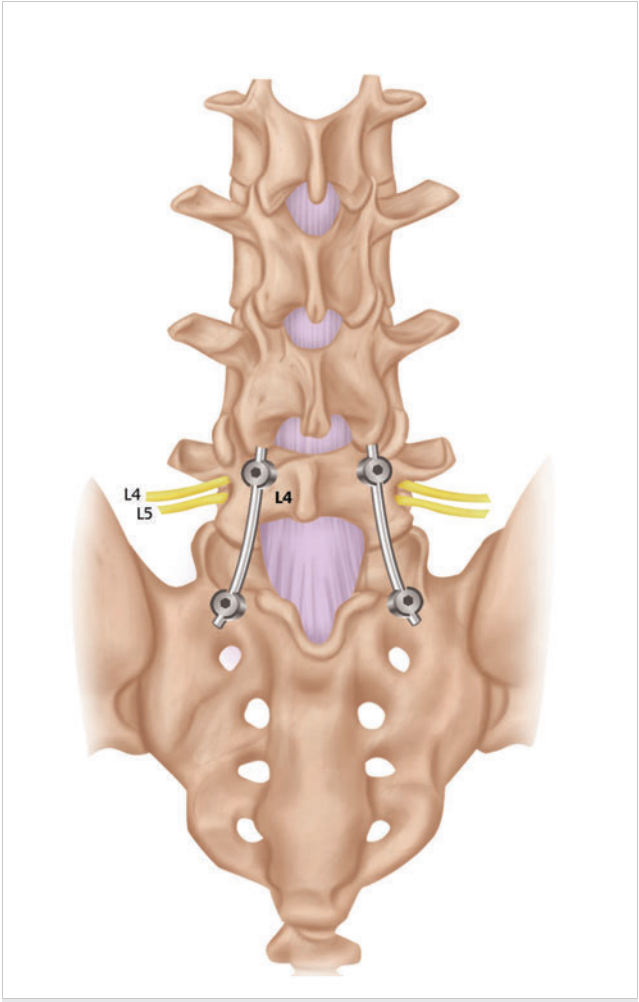

Fig. 59.6 Temporary distraction rods are removed and the L4–S1 interval is approximated as L4 is reduced onto the sacrum.

screws to a rod or plate system (▶ Fig. 59.6). As the L4 and L5 nerve roots now pass through a single neural foramen, these nerve roots must be carefully explored to ensure that they are free from tension or compression following reduction to prevent iatrogenic radiculopathy. Finally, bone graft is applied to the intertransverse region between L4 and S1.

59.11 Bailout, Rescue, and Salvage Procedures

Inability to resect the anterior L5 vertebral body requires either posterior resection of the anterior elements or acceptance of deformity. Extension of instrumention to L3 or the pelvis is sometimes necessary. Staging the procedure is safe and acceptable. Safe posterior exposure in the presence of a spina bifida or dural defect is paramount. Placement of an interbody cage during the posterior procedure is classically not recommended due to the possible need for distraction and possible increased risk of neural injury. Use of iliac crest autograft is recommended. Traditional iliac fixation, or preferably, S2 alar-iliac screws allow simultaneous crest autograft harvest and stable pelvic fixation.

Pitfalls

- During initial anterior exposure of the L5 vertebra and adjacent disks, the presacral sympathetic plexus should be located in the midline. Blunt dissection should be used to mobilize this structure laterally towards each side. It is not mandatory to directly visualize the L5 nerve roots during the anterior procedure. However, the surgeon must be knowledgeable of the location of the nerve roots in relation to the L5 pedicle and intervertebral foramen to avoid iatrogenic injury. No reduction of the deformity is attempted during the anterior approach.
- During the posterior approach, careful initial posterior spinal exposure is required to avoid dural tears due to posterior lamina dysplasia and the subcutaneous location of the posterior spinal elements.
- Use of an interbody cage is not necessary. Interbody devices elongate the anterior spinal column and may potentially increase the risk of neurologic deficit. The Gaines procedure is based on the concepts of spinal shortening and gentle realignment of neural structures.

60 Lumbosacral Interbody Fibular Strut Placement for High-Grade Spondylolisthesis: Anterior Speed's Procedure and Posterior Procedure

Michael E. Janssen, Mario R. Bran and Haitham H. Shareef

60.1 Description

Placement of an interbody fibular strut graft through the sacrum and L5 vertebral body for high-grade lumbosacral spondylolisthesis is described.

60.2 Key Principles

Placement of the strut graft fulfills the following goals in the surgical treatment of high-grade spondylolisthesis: immediate structural support and stability, solid bony interface for fusion, and a graft placed under compression.

60.3 Expectations

This procedure may be ideal for revision surgeries where the posterolateral graft bed is poor, or in the setting of a previously anterior bony strut graft procedure. The posterior placement of the graft requires a large decompression of the neural elements, which is advantageous in patients with neurologic complaints. Spinal fusion usually occurs within 3 to 6 months.

60.4 Indications

High-grade lumbosacral spondylolisthesis greater than Meyerding grade III that has failed nonoperative treatment for mechanical back pain, lumbosacral neurologic dysfunction, slip progression, or revision of previous failed surgery.

60.5 Contraindications

- Less than 50% spondylolisthesis for the posterior procedure
- High-grade lumbosacral kyphosis > 80 degrees, which may require vertebral body resection (Gaines procedure)

60.6 Special Considerations

The posterior procedure is limited by the cephalad orientation of the graft tract by the patient's body. This limits the procedure to an in situ fusion of a slip greater than 50% or the partial reduction of a higher-grade slip to 50%.

Presurgical radiographic evaluation for preoperative planning for both these procedures is essential. This includes plain films in the upright position to evaluate the posterior element dysplasia and slip angle. This defines lamina and pedicle dysplasia identifying areas at risk during decompression, and the planning of safe segmental posterior stabilization. Dysplasia of the transverse process of L4 and L5 should be evaluated for the surface area available for posterolateral fusion.

Magnetic resonance imaging (MRI) and/or computed tomography (CT) myelography should be used to evaluate the geometry and pathology of neural compression. The presence of sacral inlet stenosis should alert the surgeon to the need of a sacral dome resection. Regardless of sacral inlet stenosis, sacral dome resection may ease reduction forces required and the strain placed on the L5 nerve roots by columnar shortening.

Computed tomography angiography may be a useful adjunct to define the prevertebral vascular anatomy prior to an anterior procedure in a high-grade deformity.

60.7 Special Instructions, Positioning, and Anesthesia

The patient should be placed in the supine position for the anterior (Speed's) procedure and prone position for the posterior procedure on a radiolucent four-poster frame. Intraoperative fluoroscopy is required and neuromonitoring is strongly recommended, especially if reduction is attempted. General surgeons are part of the team for the anterior approach in certain geographic areas.

60.8 Tips, Pearls, and Lessons Learned

The graft used, autograft versus allograft, does not appear to affect outcomes in the limited literature available; however, nonvascularized grafts are less predictable in their healing abilities when compared to vascularized grafts. The vascularized-free fibular graft adds structural support as well as living bone to the fusion site and is a reasonable alternative to nonvascularized graft in locally compromised surgical beds. A section of midfibula can be removed, protecting the vascular pedicle of the fibula, so that the fibula can be folded in half to create a "double barrel" strut that allow an increase in the width of the graft, and increase of the surface area for biological incorporation.

Reduction forces may be decreased by a wide thorough decompression and sacroplasty. Resection of the iliolumbar ligament and far lateral foraminal decompression may decrease the rate of neurologic complications of the L5 root during reduction maneuvers. A commonly available cannulated reamer from an anterior cruciate ligament reconstruction set is ideal for both anterior and posterior procedures. An appropriate-size reamer can be chosen using the graft sizing tubes over the strut graft. The reamer sleeves in these sets serve as an excellent soft tissue protector.

Both the procedures can be used without supplemental posterior segmental instrumentation, but it is felt that higher rates of successful fusion can be achieved with instrumentation. This includes L4 pedicle screws, bilateral bicortical S1 fixation, and

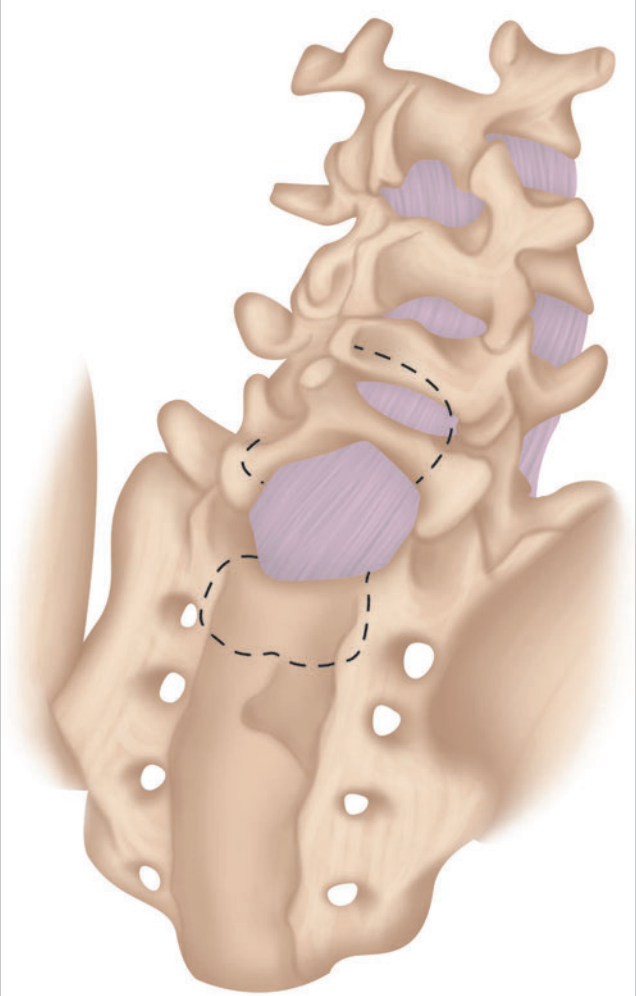

Fig. 60.1 Laminectomies at L4 (partial), L5, S1, and S2.

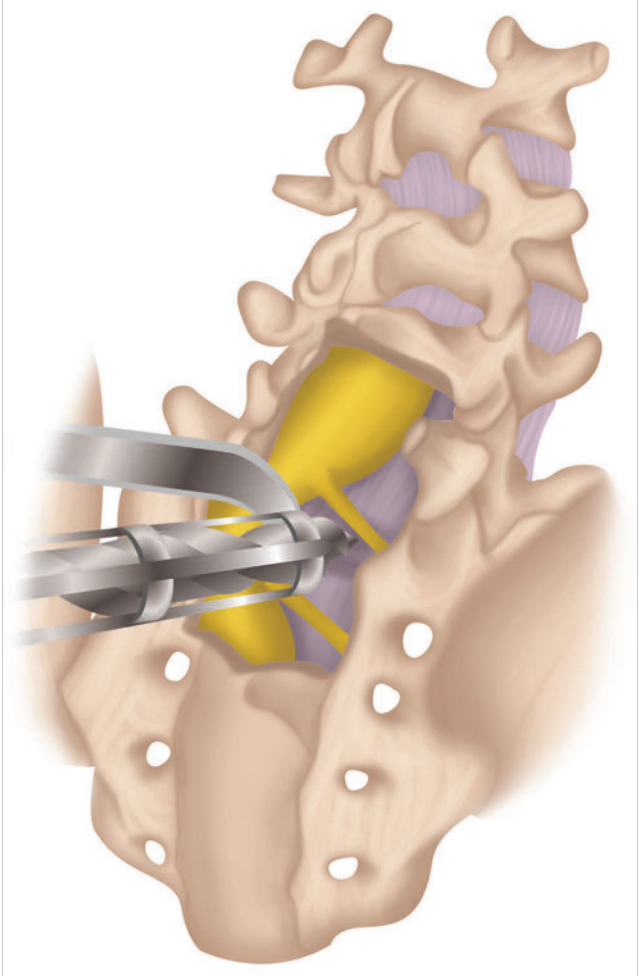

Fig. 60.2 Drilling the L5 vertebral body.

iliac screws to improve fusion rates and decrease interbody strut graft failure.

60.9 Difficulties Encountered

Complete reduction of a high-grade spondylolisthesis may not always be feasible or achievable, given the risks of neurologic deficit after reduction or the magnitude of the deformity, respectively. Reduction typically needs only to be partial to allow a reversal of the lumbosacral kyphosis. It theoretically will correct slip angle to a degree while minimizing the risks of neurologic deficit. The posterior placement of a fibular strut is limited to slips > 50% because of limitations present with the pelvis and caudad soft tissues. Anterior graft placement can be performed in partially reduced slips, but it requires some anterior resection of the L4–L5 disk for proper positioning of the guidewire and reamer.

60.10 Key Procedural Steps

The posterior placement of a strut graft requires a standard midline approach to the lumbosacral spine with exposure of the posterolateral gutters from the L5 transverse process to the sacral ala. Decompression includes partial laminectomy of the inferior portion of L4 and complete laminectomy of L5, S1, and S2 (▶ Fig. 60.1). Wide foraminal decompression of the L5 nerve roots is required. Sacroplasty is needed in the setting of sacral inlet stenosis, and may be performed to ease reduction. This is best achieved with a broad curved osteotome under direct visualization. If instrumentation is to be used, it should be placed prior to reduction or graft placement. This typically requires fixation from L4 to the sacrum and in most instances the pelvis.

The starting point for the guide pin is typically midway between the S1 and S2 nerve roots and 8 mm from the lateral edge of the spinal canal. It is essential to gently retract the thecal sac and nerve roots out of harm's way with a smooth retractor or by placement of smooth Kirschner wires into the sacrum for static retraction. The guide pin is placed from lateral to medial under constant fluoroscopic monitoring (▶ Fig. 60.2). The goal is to have the guide pin tip in the center of the L5 body on anteroposterior imaging, and the superoanterior quadrant of the L5 body on the lateral projection (▶ Fig. 60.3). The reamer depth should be directly measured off the guide pin, but the length of graft should be approximately 5 mm shorter to facilitate recessing the graft 2 mm below the sacral cortex (▶ Fig. 60.4). Partial reduction should be done prior to

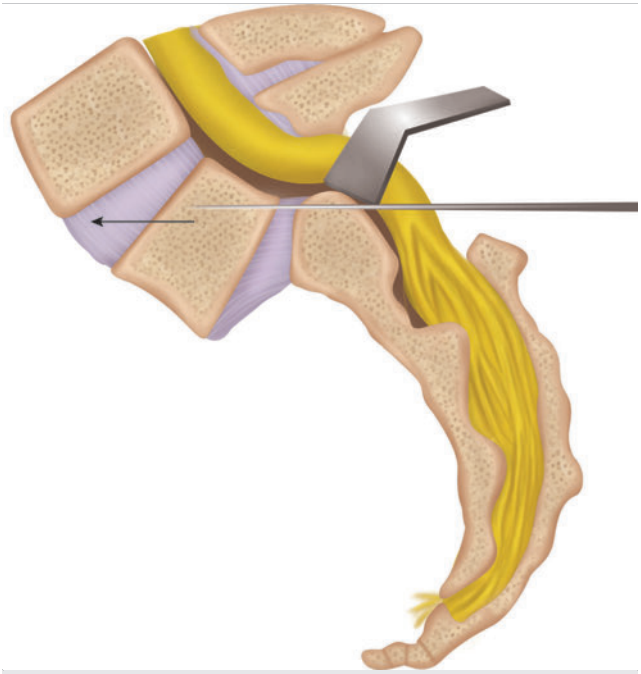

Fig. 60.3 Sagittal plane orientation of the guide pin.

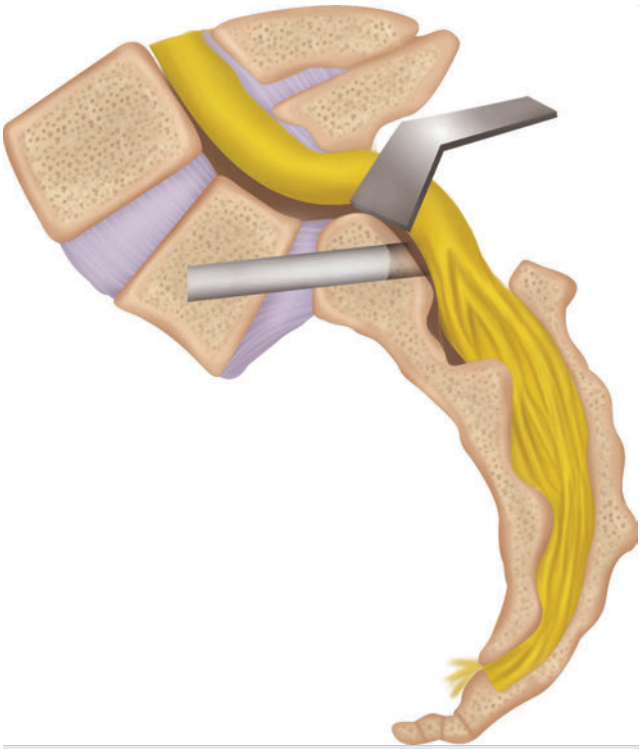

Fig. 60.4 Sagittal view of the lumbosacral junction showing the fibular graft in place.

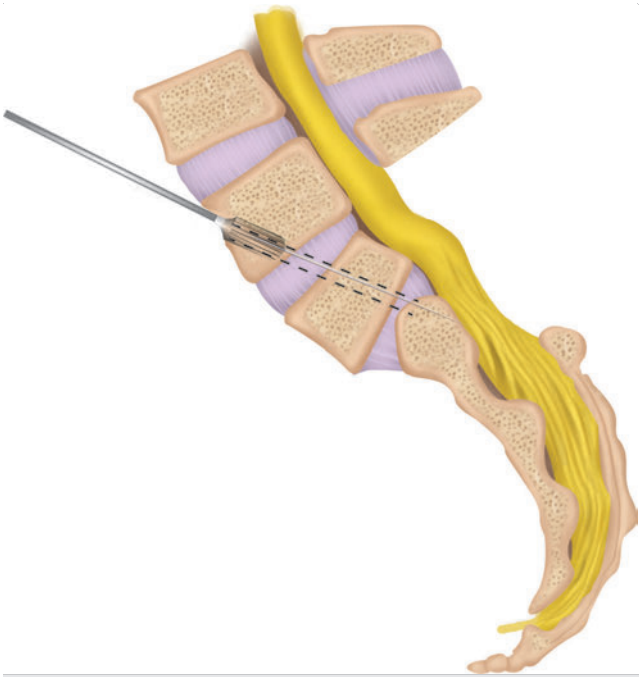

Fig. 60.5 Drill path through the spondylolisthesis.

preparation and placement of the graft. The reduction can be facilitated and held by segmental instrumentation placed at the beginning of the procedure.

The anterior procedure can be performed as a stand-alone procedure for primary or revision procedures. A significant reduction of the slip can be performed by a posterior decompression, segmental instrumentation, and reduction procedure prior to anterior graft placement. If a significant reduction is achieved, then a partial L4–L5 disk removal is necessary to access the proper starting point on the L5 body. A guidewire is then drilled through the middle of the midaspect of the cephalad end plate of L5, across the L5 vertebral body and the L5–S1 disk space, docking into the S1 body at the hypoplastic S1–S2 disk level. The guide pin is placed under constant fluoroscopic guidance.

A modified technique is performed exposing the L4–L5 disk, which is completely removed, placing the graft in a more perpendicular way to the S1 end plate, close to 90 degrees, which allows more efficient interfragmentary compression and superior protection from shearing forces. A trapezoidal femoral ring allograft is placed into the L4–L5 disk space covering the entry portal of the fibular strut graft in the L5 end plate. The reminder of the procedure is similar to the posterior procedure (▶ Fig. 60.5).

For both procedures tapering the leading end of the graft can decrease the amount of force needed for graft placement.

60.11 Bailout, Rescue, and Salvage Procedures

If the thecal sac cannot adequately be mobilized, consider a more lateral starting point. Placing the graft through the S1 pedicle is a viable bailout. Graft fracture during posterior placement can be salvaged with an anterior procedure. If a strut graft cannot be placed, a posterolateral fusion can be performed from L4 to pelvis.

Pitfalls

- Aggressive retraction of neural elements, especially without proper mobilization of the dural sac
- Dural tears with the use of power equipment
- Guidewire binding within the reamer, with migration into surrounding structures

61 Rib Expansion Technique for Congenital Scoliosis

Robert M. Campbell, Jr.

61.1 Description

This technique is designed to lengthen the concave constricted hemithorax through vertical expandable prosthetic titanium rib (VEPTR) expansion thoracoplasty with correction of congenital scoliosis to maximize the potential for thoracic growth to benefit the underlying lungs. Unilateral unsegmented bars grow at a rate of 7% a year when treated by VEPTR, contributing to increased thoracic spinal height and thoracic volume which results in increased lung volume for the growing child.

61.2 Expectations

With VEPTR II expansion thoracoplasty, one can stabilize or correct rigid congenital scoliosis, without the growth inhibition effects of spine fusion, and enlarge the constricted concave hemithorax with probable benefit for the underlying lung. The thoracic spine can grow with further increase in thoracic volume. Additional benefits include leveling the shoulders, and improving both head and truncal decompensation.

61.3 Indications

Indications include progressive thoracic congenital scoliosis, in a patient aged 6 months up to skeletal maturity, with three or more fused ribs at the apex of the concave hemithorax, greater than 10% reduction in space available for lung, and having progressive thoracic insufficiency syndrome. Thoracic insufficiency syndrome is identified by the inability of the thorax to support normal respiration or lung growth. VEPTR I was originally approved as a Humanitarian Use Device (HUD) in 2004, requiring monitoring by IRBs and restricted in use to 4,000 new patients/year, but recently the FDA cleared the VEPTR for use under 510(k) designation, allowing use of the VEPTR without the need for IRB monitoring, with indications based on the discretion of the surgeon without restriction on the number of new patients/year. The device also has undergone modifications, and a VEPTR II version is now available with the primary difference being the presence of the addition of a rod proximally, which enables contouring to accommodate thoracic kyphosis of the ribs (▶ Fig. 61.1a).

61.4 Contraindications

- Inadequate soft tissue coverage for devices
- Poor rib bone stock or absence of proximal ribs for attachment of devices
- Absent diaphragmatic function
- Active pulmonary infection
- Inability to undergo repetitive episodes under general anesthesia

61.5 Special Considerations

Preoperative magnetic resonance imaging (MRI) of the entire spinal cord is advised to rule out associated spinal cord pathology. An echocardiogram is performed to rule out congenital heart disease; a preoperative respiratory syncytial virus screen is also advised.

61.6 Special Instructions, Positioning, and Anesthesia

Patients are placed in the prone position (▶ Fig. 61.1). Somatosensory evoked potentials and motor evoked potentials of extremities are monitored during surgery. A central line and arterial catheter are recommended.

61.7 Tips, Pearls, and Lessons Learned

To increase the necessary soft tissue coverage, an oral appetite stimulant, cyproheptadine (Periactin, Merck & Co.), tube feeding, or gastric percutaneous endoscopic gastrostomy (PEG) feedings are useful. A body weight at the 25th percentile of normal, or greater, reduces the risk of skin slough over devices. The superior VEPTR cradle site should be placed at the superior aspect of the curve, but not into the flexible spine above it because of the risk of a proximal compensatory curve. Acute thoracic outlet syndrome can be encountered with closure because of the altered proximal thoracic anatomy, so both pulse oximeter and upper extremity evoked potentials are monitored for loss of signal, and any changes are addressed by altering closure to let the scapula retract itself more proximal.

61.8 Key Procedural Steps

A modified thoracotomy incision is made with the distal portion carried anteriorly in line with the 10th rib (see ▶ Fig. 61.1b). The paraspinal muscles are reflected medially to the tips of the transverse processes, with care taken not to damage the rib periosteum (▶ Fig. 61.1c). The VEPTR II (Depuy-Synthes) is now ready for insertion. The superior VEPTR cradle is first placed adjacent to the tips of the transverse processes of the spine around two ribs or a fused rib mass (▶ Fig. 61.1d). Next, the opening wedge thoracostomy is performed at the apex of the fused chest wall. Usually, there is a fibrous cleft present anteriorly in the fused ribs in line with the planned thoracostomy. This is released with cautery, with a no. 4 Penfield retractor inserted to protect the underlying pleura; then, the thoracostomy is continued with a Kerrison rongeur, cutting a channel transversely through the rib fusion mass up to the transverse processes (▶ Fig. 61.2a). The osteotomized interval is gently expanded with lamina spreaders (▶ Fig. 61.2b), and a Kidner sponge in a clamp is used to strip the pleura down proximal and distal. Any bone bridge remaining medial is carefully resected with a rongeur. The fused bone adjacent to the spine should be carefully pulled out laterally with a curved curette

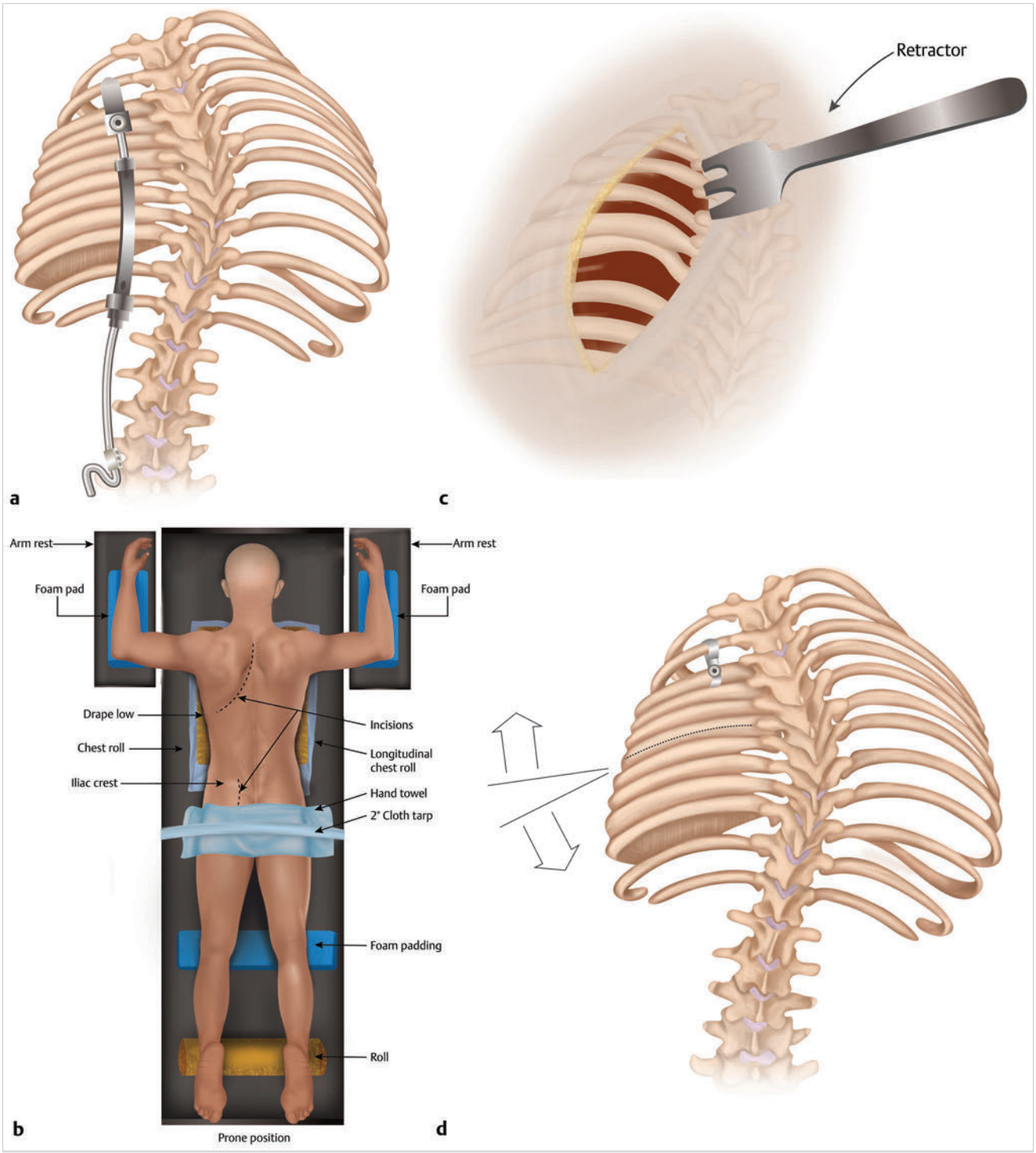

Fig. 61.1 **(a)** VEPTR II: The proximal rod can be contoured to accommodate kyphosis of the proximal thorax (**b**) The positioning details and the modified thoracostomy incision for VEPTR II opening wedge thoracostomy. (**c**) The paraspinal muscles are reflected to the tips of the transverse processes of the spine. The "safe zone "for superior VEPTR II rib cradle insertion (arrow) is posterior to the scalene muscles with the neurovascular bundle anterior. (**d**) The VEPTR II rib cradle is placed at the superior aspect of the curve with the planned rib fusion osteotomy distally.

to avoid spinal cord injury. A second opening wedge thoracostomy, paralleling the first more distally, may be necessary when there is broad expanse of fused ribs of the hemithorax. The opening wedge thoracostomy is held open with a special rib retractor, and VEPTR II devices are implanted to stabilize the hemithoracic correction.

In patients younger than 18 months, the spinal canal is too small for a spinal hook, so a single rib-to-rib VEPTR device is implanted on the ribs just adjacent to the spine. An inferior VEPTR II cradle site is prepared on a stable, relatively horizontal rib, usually the 9th or 10th rib, and then the VEPTR is implanted and tensioned (▶ Fig. 61.2c).

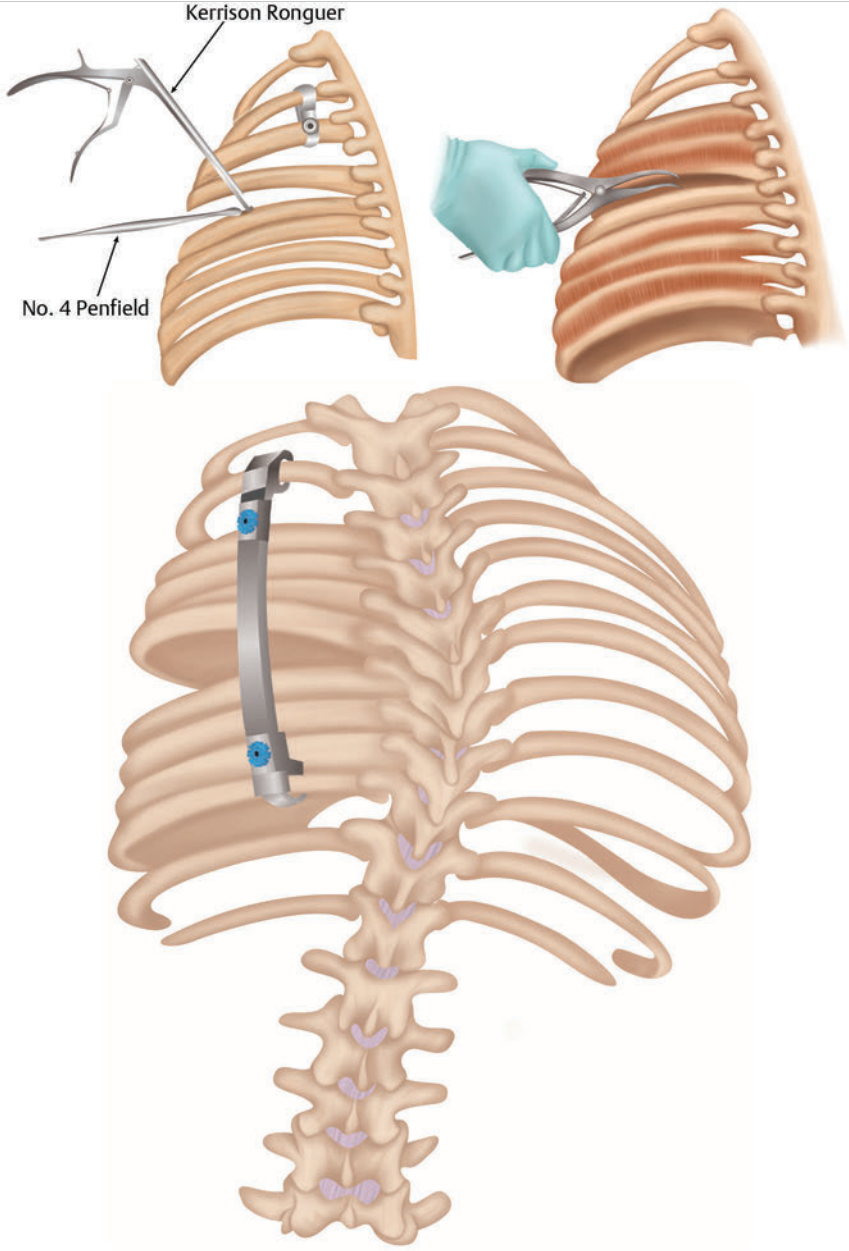

Fig. 61.2 (**a**) The opening wedge thoracostomy starts laterally in a natural rib cleft, with a no.4 Penfield retractor inserted underneath the rib fused mass to protect the lung, with the Kerrison ronguer used to cut a slot lateraly to medially to complete the opening wedge thoracostomy. (**b**) The opening wedge thoracostomy is slowly opened by a laminar spreader(arrows). The constricted hemithorax is thus lengthened by the opening wedge thoracostomy with indirect correction of the congenital scoliosis. **(c)** A rib-to-rib VEPTR II is implanted to stabilize the thoracic deformity correction.

In patients older than 18 months, the spinal canal is large enough for a spinal hook, so a hybrid VEPTR II from ribs to spine is used for more forceful correction (▶ Fig. 61.3). A longitudinal skin incision is made at the selected level of the lumbar spine, usually L2–L3, and a two-level unilateral exposure is made for insertion of a single lamina hook. Care is taken to be below any areas of junctional kyphosis. With the hemithorax deformity corrected by the rib retractors across the thoracostomy, the hybrid VEPTR II size is chosen. The expandable portion of the hybrid should end at T12 and the spinal rod should be cut to extend distally only 1.5 cm past the lumbar hook. To safely form a tunnel in the muscle for the device between incisions, a Kelley clamp is threaded from the proximal incision into the lumbar incision, and used to pull a no. 20 chest tube back into the proximal wound. The VEPTR II hybrid rod end is threaded into the chest tube proximally and the tube is used to guide the device into the distal wound. The hybrid VEPTR II is attached to the superior cradle, then the hook, and is then distracted. A second rib-to-rib VEPTR device is usually placed in the posterior axillary line to assist in expanding the constricted hemithorax. The medial hybrid device is once again distracted a final time. **Video 61.1** shows further detail about this technique.

Closure is in the usual thoracotomy fashion, but first the musculocutaneous flaps are stretched to perform closure without tension. Utilize a chest tube if there is a large pleural rent, adding two round Jackson-Pratt drains, a no. 7 and a no. 10, along with a deep pain catheter for ropivacaine infusion. There is a 50% risk of a transfusion because of the dead space beneath the large flaps created. The chest tubes are removed when drainage is less than 1 cc/kg/d, and Jackson Pratt drains are removed when the drainage for each is 20 cc or less per day. No bracing is used. Patients are mobilized to ambulation as soon as tolerated. Postoperative assessment should include standing anteroposterior (AP) and lateral radiographs of the spine.

The devices are lengthened on schedule every four to six months in outpatient surgery (▶ Fig. 61.4). Device expansion access is made with 3-cm skin incisions, the distraction locks are removed, and the devices are extended slowly over several minutes, stopping when the reactive force is excessive. Expansion can be as minimal as 0.5 cm in a very tightly constricted chest and as much as 2.0 cm when the patient has had a growth spurt. Replacement of completely expanded devices can be done through limited incisions.

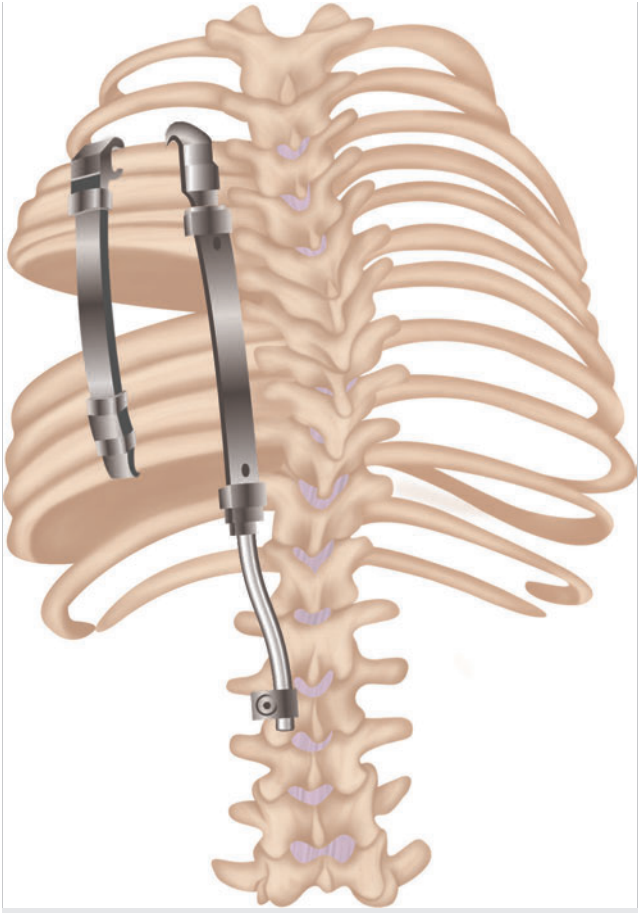

Fig. 61.3 A hybrid rib-to-rib vertical expandable prosthetic titanium rib construct.

61.9 Bailout, Rescue, and Salvage Procedures

When there are no proximal ribs for VEPTR attachment, this can be addressed by a first-rib reconstruction through longitudinally osteotomizing the clavicle, bringing the anterior portion as a vascular pedicle underneath the brachial plexus, and joining it to an autograft rib from the contralateral side that is then attached to the spine. Within 3 months, the reconstructed first rib usually has healed enough for a device attachment. When there are inadequate posterior spinal elements for hybrid VEPTR hook attachment or severe pelvic obliquity is present, then a hybrid rib-to-pelvis attachment through a 90 degree S-hook can be considered (▶ Fig. 61.5). A longitudinal incision is made over the posterior superior iliac spine and the abductors are reflected by cautery. A 1-cm transverse incision is made by cautery just above the apophysis at the junction between the posterior third and the middle third of the iliac crest. The S-hook is then placed though the incision above the apophysis, just lateral to the sacroiliac (SI) joint, and is mated by a domino coupling to the hybrid device. The device is then distracted.

Pitfalls

- Inadequate correction of the thoracic deformity in the initial implant surgery cannot be addressed by expanding the devices later. Every effort should be made to completely correct the asymmetry between the concave and convex hemithorax with the initial procedure.
- Vertical expandable prosthetic titanium rib complications include skin slough, device infection, and asymptomatic migration devices. Skin slough is treated by debridement

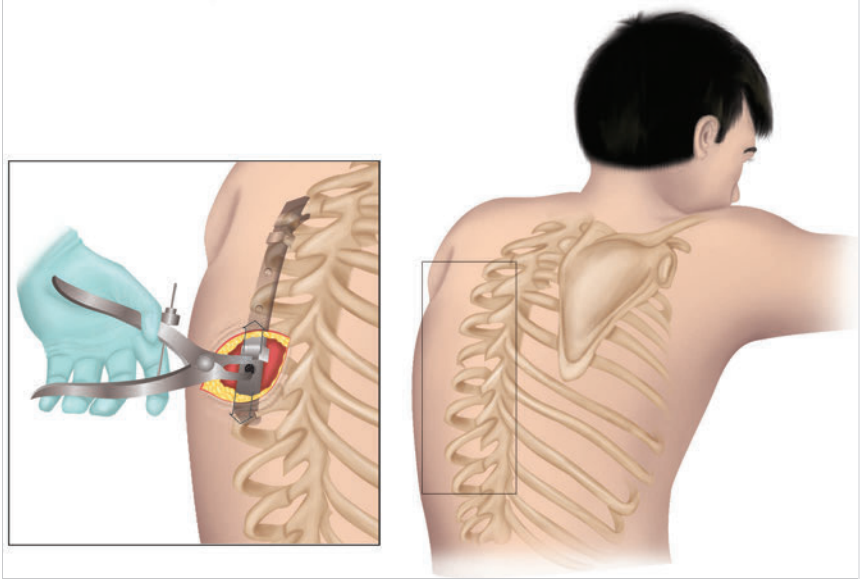

Fig. 61.4 The VEPTR lengthening is done through a 3 cm incision every 4-6 months.

and primary closure. Sometimes, it is necessary to use soft tissue expanders to provide skin coverage over the devices. Infections can be resolved by debridement and irrigation with loose approximation of the wound to allow granulation tissue to cover devices. Recurrent infections are best addressed by temporary removal of the central portion of the devices, with reinsertion done once the infection is resolved. Upward migration of the superior rib cradle can usually be addressed by re-anchoring it to the reformed rib of original attachment through a limited exposure. Spinal hooks that have migrated distally can be reseated at a lower level. S-hooks migrating distally into the pelvis can be removed when approaching the acetabulum, and then re-anchored onto reformed superior iliac crest.

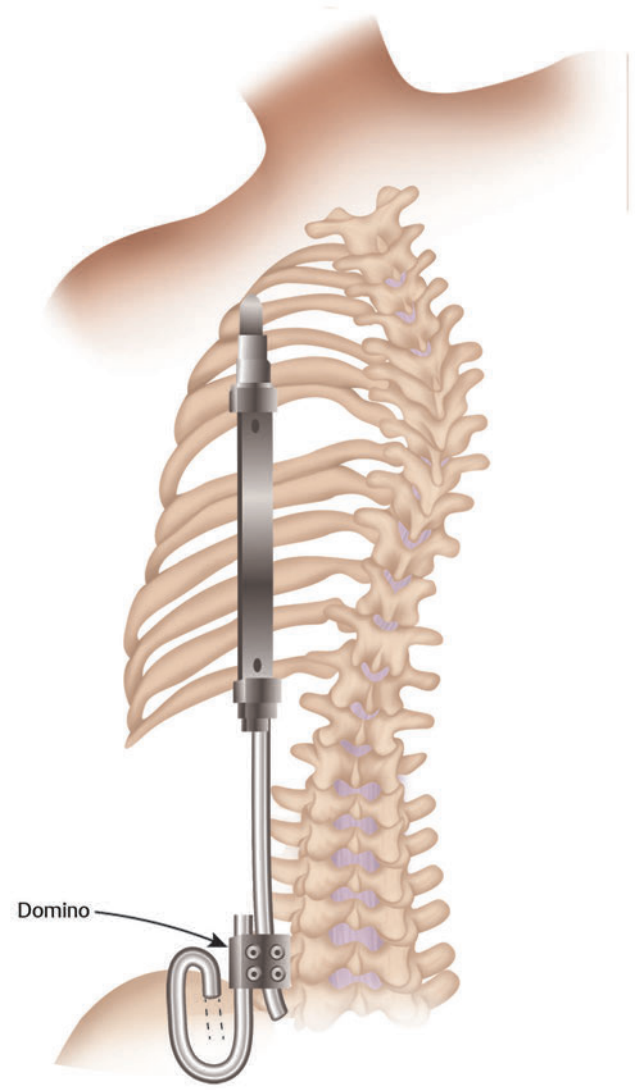

Fig. 61.5 When there is inadequate posterior spinal elements for a spinal hook, or severe pelvic obliquity is present, then an S-hook to the pelvis attached to the hybrid VEPTR can be used to correct the spinal deformity.

62 Vertebral Body Stapling and Vertebral Body Tethering for Spinal Deformity

Joshua M. Pahys, Patrick J. Cahill, Amer F. Samdani, and Randal R. Betz

62.1 Description

Vertebral body stapling (VBS) and anterior vertebral body tethering (VBT) are two methods of regulating spinal curvature development in skeletally immature patients with scoliosis. This can be accomplished using traditional open or minimal access approaches.

62.2 Key Principles

Vertebral body stapling and VBT rely on principles similar to the long accepted treatment of physeal staples for limb malalignment in skeletally immature children. This growth modulation allows for continued curve correction after surgery in an effort to minimize or prevent the need for brace treatment or spinal fusion in patients at high risk for curve progression.

62.3 Expectations

Ideally, a surgeon with experience in anterior spine surgery, especially using minimally invasive surgery (MIS) techniques, should be able to perform this procedure. It may be helpful to enlist the aid of a general or thoracic surgeon. With the use of these techniques, scoliotic vertebrae from T4–L3 can be stapled or tethered.

62.4 Indications

62.4.1 Vertebral Body Stapling

Candidates for VBS include skeletally immature patients with thoracic, thoracolumbar, and/or lumbar scoliosis curves (Risser 0–2, Sanders digital score ≤ 4) with thoracic coronal curves measuring 20–35 degrees and lumbar curves measuring 20–45 degrees that ideally bend to < 20 degrees.

62.4.2 Vertebral Body Tethering

Candidates for VBT include skeletally immature patients with thoracic, thoracolumbar, and/or lumbar scoliosis curves (Risser 0–2, Sanders digital score ≤ 4) with thoracic coronal curves measuring from 30 to 60 degrees and lumbar curves measuring from 30 to 60 degrees that ideally bend to < 30 degrees. The upper thoracic curve itself in Lenke 2 and 4 curves is not treated; one can expect 50% spontaneous correction.

62.5 Contraindications

We have not performed these procedures for congenital scoliosis, most forms of neuromuscular scoliosis, or scoliosis related to skeletal dysplasias. We do not perform these procedures in patients who have true hyperkyphosis (> 40–50 degrees), as these procedures tend to induce further kyphosis. Medical contraindications are the same as for any anterior spine or chest procedure and include systemic infection, active respiratory disease, or conditions with increased anesthetic risk. Vertebral body stapling for thoracic curves > 35 degrees or in those that do not correct to < 20 degrees on bending films has yielded poor results. This limitation prompted the development and implementation of VBT. We have not performed VBT in children younger than 9 years of age out of concern for potential overcorrection.

62.6 Special Considerations

When performing thoracoscopic VBS/VBT in small children (weighing < 50 pounds), it may be difficult for the anesthesiologist to obtain or maintain single-lung ventilation. The child's airway size may not be compatible with the limited sizes of endotracheal tubes available. In these cases, carbon dioxide (CO_2) insufflation for the thoracoscopic portion may be used, with intrathoracic pressures from 7 to 10 mm Hg. Higher pressures can produce adverse hemodynamic effects (e.g., tachycardia or hypotension).

Despite having previous experience with anterior spinal surgery, we performed the first 10 thoracic VBT procedures via a mini-thoracotomy (10 cm at T9–T10) with thoracoscopic assistance to gain comfort and familiarity with the implant system and technique. The thoracotomy assists with three-dimensional (3D) direction of the screws and observation and palpation of the screw tip on the contralateral side of the vertebral body. All thoracic VBT procedures have been subsequently performed with an all-thoracoscopic approach, with equal 3D curve correction compared to the open technique.

62.7 Special Instructions, Positioning, and Anesthesia

A double-lumen endotracheal tube is preferred to achieve single-lung ventilation during the procedure. The patient is placed in the lateral decubitus position on a radiolucent table with the convex side up. The table is not flexed, and a small axillary roll is used.

62.8 Tips, Pearls, and Lessons Learned

62.8.1 Vertebral Body Stapling

An important principle of VBS insertion is to have the tines of the staples parallel and adjacent to the vertebral body end plates. Staple tine deployment usually occurs over 1 to 2 minutes. The staples should be placed in the inserter, with the

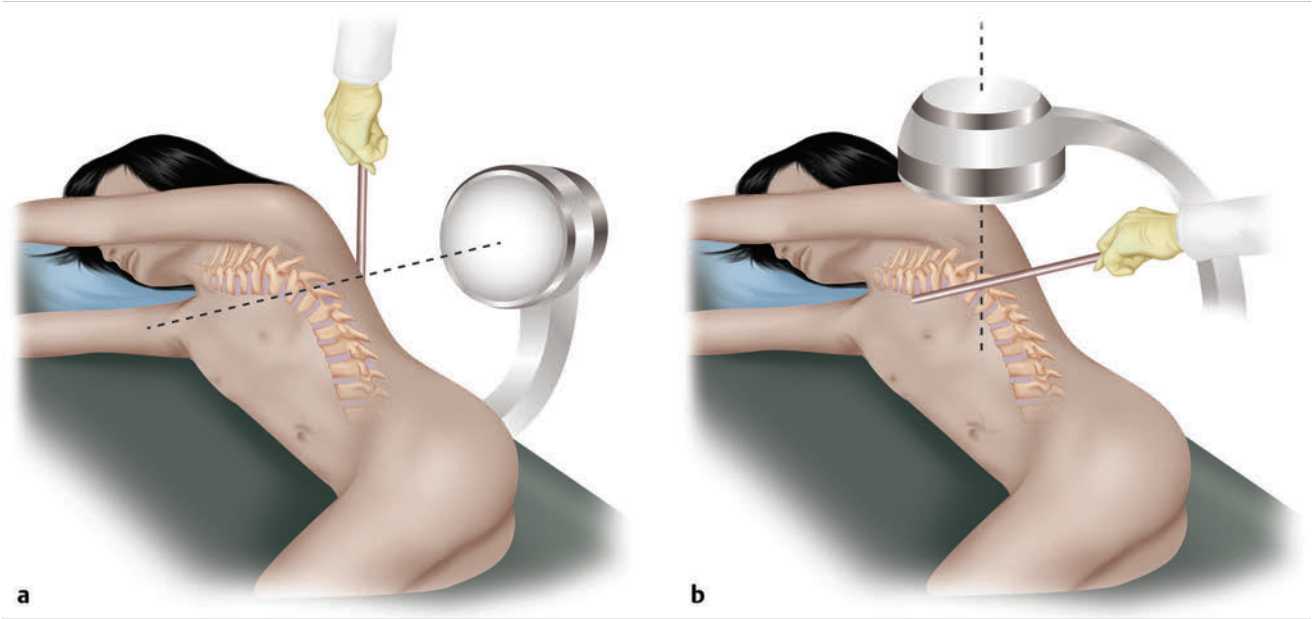

Fig. 62.1 **(a)** The patient is placed in a lateral decubitus position. Using fluoroscopic imaging, the levels of the spine to be instrumented are confirmed. An anteroposterior film determines the cranial/caudal extent of the vertebrae. (**b**) A lateral/medial fluoroscopy image is used to confirm the vertebral levels to be instrumented and to center the portals in the posterior axillary line.

tines straightened, and immersed in the sterile ice bath until the moment of insertion. Using portal sleeves or a nasal speculum to maintain open portals allows for quick passage of the staples while protecting the skin and muscle. If tine deployment is occurring as the staple is being driven into the body, it is essential that the surgeon stop, as the tines may curl enough to penetrate the disk space. If this occurs, the staple should be removed, re-iced, and then reinserted.

With the patient positioned in the lateral decubitus position, the flexible, main thoracic curve reduces in magnitude. Intraoperative correction is critical to get the coronal curve below 20 degrees on the first erect radiograph, which has resulted in significantly higher success rates. The dull VBS trial may be used to push at the apex of the convexity, further reducing the curve prior to staple impaction. The staple inserter can also be kept on the adjacent staple and used to push and further translate the spine during VBS placement of the next most caudal level.

To obtain continued curve correction, most patients now are requested to wear a nighttime corrective brace such as a Providence brace.

62.8.2 Vertebral Body Tethering

When a thoracotomy is performed, the surgeon's hand can be placed onto the opposite side of the spine to assess when the tap and screw have breached the contralateral cortex to achieve bicortical fixation. This also ensures that there are not more than 2 to 3 mm protruding on the contralateral side to limit any significant impingement on the aorta. When a thoracoscopic-only approach is utilized, proper positioning and cortical purchase is monitored in a stepwise fashion using fluoroscopy. The thoracoscope can also be placed in one of the portals in line with the screws to better appreciate the anteroposterior screw placement and trajectory. After all screws have been placed, we generally confirm proper VBT screw length and trajectory with intraoperative reconstructed axial images from a specialized fluoroscopy machine or intraoperative computed tomography (CT) scanner if available.

Patients wear a noncorrecting soft thoracolumbosacral orthosis (TLSO), and activities are restricted for 6 weeks after VBS/VBT. At our institution, the rate of staple loosening or breakage is < 1% with normal activities or vigorous participation in sports, including gymnastics.

62.9 Key Procedural Steps

It is recommended to include all vertebrae that lie within the Cobb angle of the curve for VBS and VBT, which can safely include from T4–L3.

If video-assisted thoracoscopy is being utilized for insertion, then one-lung ventilation will be necessary unless CO_2 gas insufflation is available to displace the lung for visualization of the spine and surrounding structures. After positioning the patient, biplanar fluoroscopy is used to determine the exact location for the intercostal portals along the posterior axillary line before the patient is prepped and draped (▶ Fig. 62.1, ▶ Fig. 62.2). Through each skin incision it is possible to make 2 to 3 internal intercostal portals. This allows several levels to be instrumented through each skin incision. Thoracoscopic portals (for VBT) or nasal speculum distractors (for VBS) can be used to maintain the intercostal space and protect the muscle and pleura during implant placement. In the lumbar spine, tubular retractors and a minimally invasive retroperitoneal lateral approach to the spine can be used, as well as a small open standard retroperitoneal approach. Incisions for the lumbar approach are also localized based on the image intensifier. Each incision should allow for three lumbar levels to be accessed. We prefer to place VBS/VBT by retracting the psoas posteriorly past

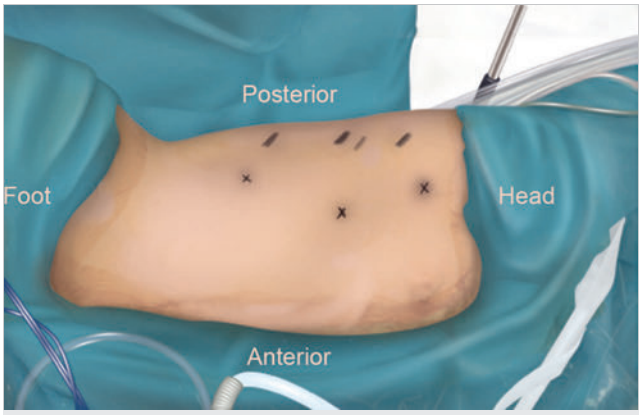

Fig. 62.2 Generally, two to three 5-mm incision portals (X's) in the intercostal spaces are placed in the anterior axillary line for the scope and harmonic scalpel, while two to three 15-mm portals are placed in the posterior axillary line over the levels to be instrumented.

the midline of the vertebral body rather than via a transpsoas technique. However, with good electromyographic monitoring, a transpsoas insertion of the VBS or VBT can be performed.

62.9.1 Vertebral Body Stapling

Using fluoroscopy, the appropriate-size staple trial is selected to span the distance across the disk, apophyses, and physes. The desired location in the vertebral body for the tines is as close to the end plates as possible. Once the correct size for the trial is determined, it is tapped into place where the staple is to be placed. Ideally, one four-prong staple is placed at each level, but in very small children, the most proximal vertebra is often small, and a single prong staple may be necessary. If the tines of the trial come close to the segmental vessels, then the pleura is incised and the vessels are retracted gently while the pilot holes are created and until the staple is seated in place.

The pilot holes act as a guide for the staple tines to ensure correct placement. The trial is removed, and the cooled, straightened staple is quickly inserted. Once the staple is in the desired position (▶ Fig. 62.3), the staple inserter is removed and an impactor is used to drive the staple deeper prior to tine deployment.

Staples are placed anterior to the rib heads, and if the patient has severe hypokyphosis or thoracic lordosis, an additional single staple can be placed more anterior on the vertebrae to help produce kyphosis with the patient's growth. In the lumbar spine, the staples should be placed in the posterior half of the body to maintain a normal lordosis.

62.9.2 Vertebral Body Tethering

The setup and portal placement for VBT is similar to VBS as described above. However, the VBT screws must be placed in the center of the vertebral body, which requires reflection of the parietal pleura off the lateral aspect of the vertebral body and division of the segmental vessels, all of which can be performed with a harmonic scalpel. Standard 15-mm thoracoscopic portals can accommodate all VBT instruments/implants, while maintaining appropriate intrathoracic CO_2 pressure.

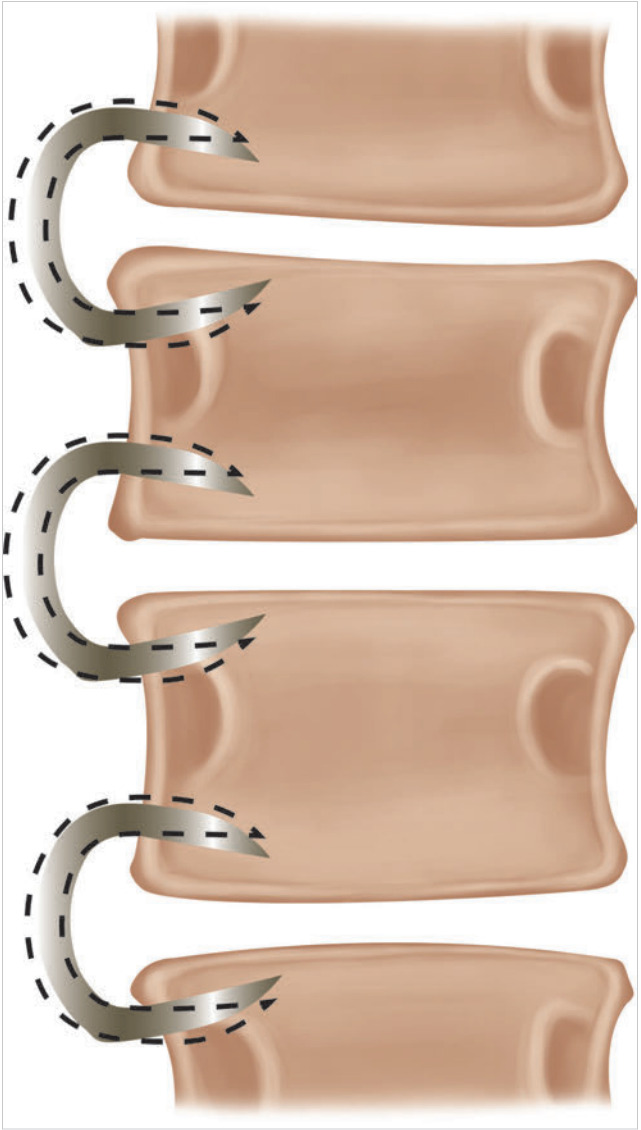

Fig. 62.3 After the staple is inserted, the position is confirmed with fluoroscopic image. It is important to note that the staple tines have deployed and have not penetrated the end plate.

A three-pronged staple is malleted into place anterior to the rib head and confirmed with fluoroscopy. The screw hole is tapped with a 5.2-mm tap in a lateral fashion to achieve a bicortical hole. The length is measured and the screw is placed under fluoroscopic guidance. Placement of the thoracoscope in one of mid/posterior axillary line portals is helpful to gauge the proper anteroposterior trajectory.

The tether is then laid into the tulips of all screws after their proper position has been confirmed fluoroscopically. The set screw is tightened on the most cephalad screw first. A tensioner is then placed onto one of the two most caudal screws to apply progressive tension to the rope across the entire construct. Translation forces are then applied to the adjacent cranial and caudal screws to improve overall correction when securing the tether into each level. A thoracoscopic compressor can also be utilized in addition to translation at each level, which we have found dramatically increases curve correction. The tether is

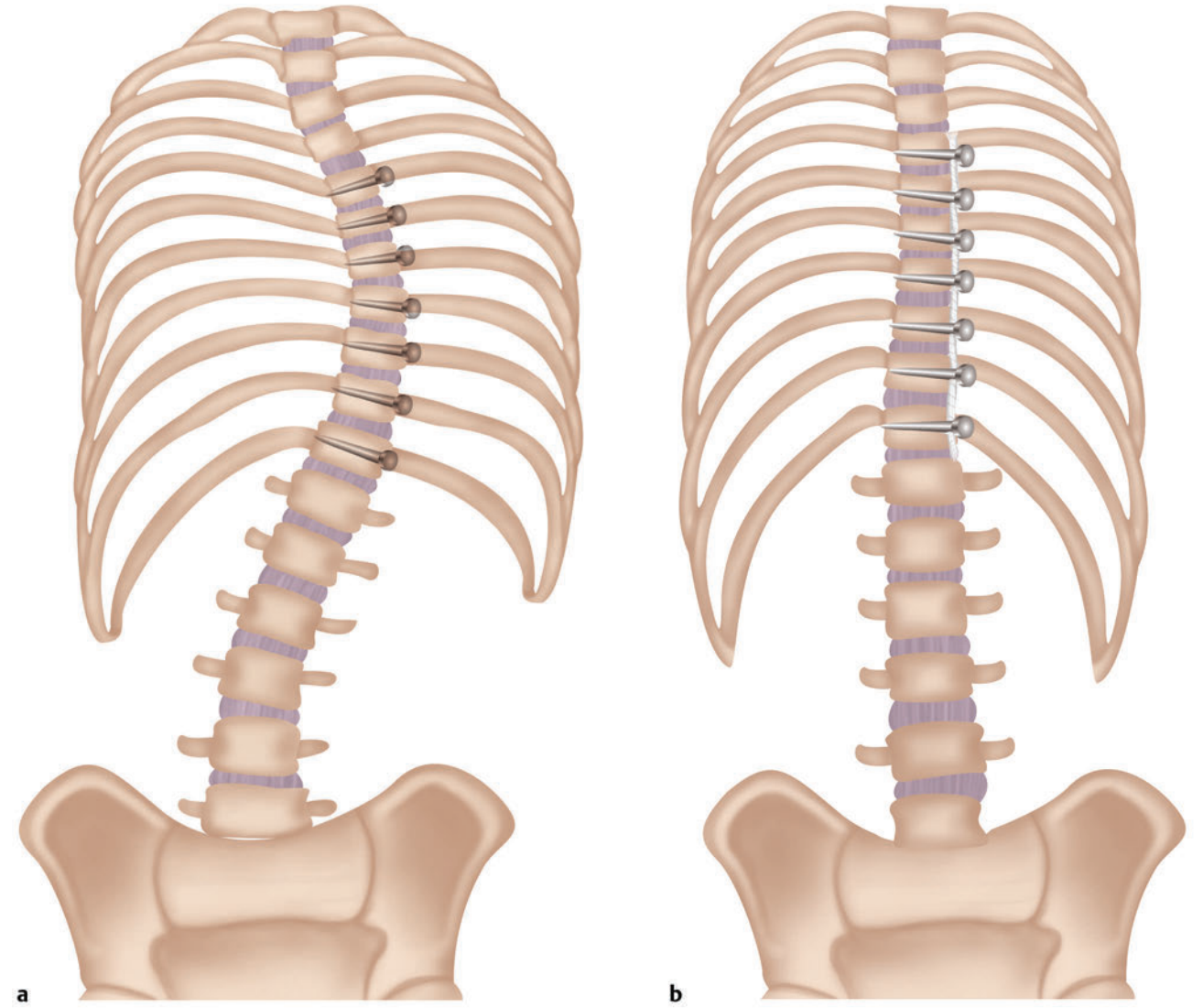

Fig. 62.4 **(a)** Screws have been placed through the three-prong staple across the vertebral body to achieve bicortical purchase. (**b**) The tether is laid into the tulips of the screws. Deformity correction is obtained by tensioning the tether as well as translational and derotational forces applied to each successive screw in a cranial to caudal fashion.

progressively locked into the next most distal screw as the above maneuvers are repeated at each level. After all set screws are locked, the residual tether is cut with the harmonic scalpel. Approximately 2.5 cm of tether are left at both ends to permit adjustments in the future if needed (▶ Fig. 62.4).

Final radiographs or fluoroscopy images are taken to ensure good position of the implants prior to closure. The incisions should be closed in the surgeon's routine manner. A chest tube or tubes are placed.

62.9.3 Bailout, Rescue, and Salvage Procedures

If the deformity is too large or inflexible for VBS, VBT is an excellent alternative. If VBS/AVBT is unsuccessful in arresting curve progression, traditional posterior spinal fusion (PSF) using pedicle screws can be safely performed with excellent results. We have not performed a PSF after VBT to date, but safe placement of posterior pedicle screws has been performed after anterior fusion with screws and is certainly feasible, if necessary.

Pitfalls

- In VBS, if segmental vessels are close to the staple tine, then proactively incise pleura parallel to the vessel and mobilize it.
- If anatomical structures prevent the instrumentation of the entire curve (e.g., T4, T5, or L3), then VBS/VBT should be placed where possible.
- The unstapled/tethered portion of the curve may behave differently and should be observed to see if bracing is needed.

63 Posterior Rib Osteotomy for Rigid Coronal Spinal Deformities

Venu M. Nemani, Oheneba Boachie-Adjei, and Bernard A. Rawlins

63.1 Description

This technique is designed to provide additional mobility (release) to the spinal elements in a rigid deformity.

63.2 Key Principles

The level of release should include the rib of the apical vertebrae and ribs caudal and cephalad, depending on the curve magnitude.

63.3 Expectations

Concave rib osteotomies provide additional release to the spine beyond that provided by facetectomies, anterior diskectomies, and convex rib thoracoplasty. This becomes apparent during translation maneuvers using sublaminar wires.

63.4 Indications

Rigid coronal curves in adult and pediatric deformities

63.5 Contraindications

Severe pulmonary deficit, for which surgery to both pulmonary cavities would compromise the patient's perioperative recovery

63.6 Special Considerations

Pulmonary function testing preoperatively is usually done in large curves and provides an assessment of pulmonary reserve.

63.7 Special Instructions, Positioning, and Anesthesia

Positive pressure ventilation should be requested to evaluate air leaks following the osteotomies.

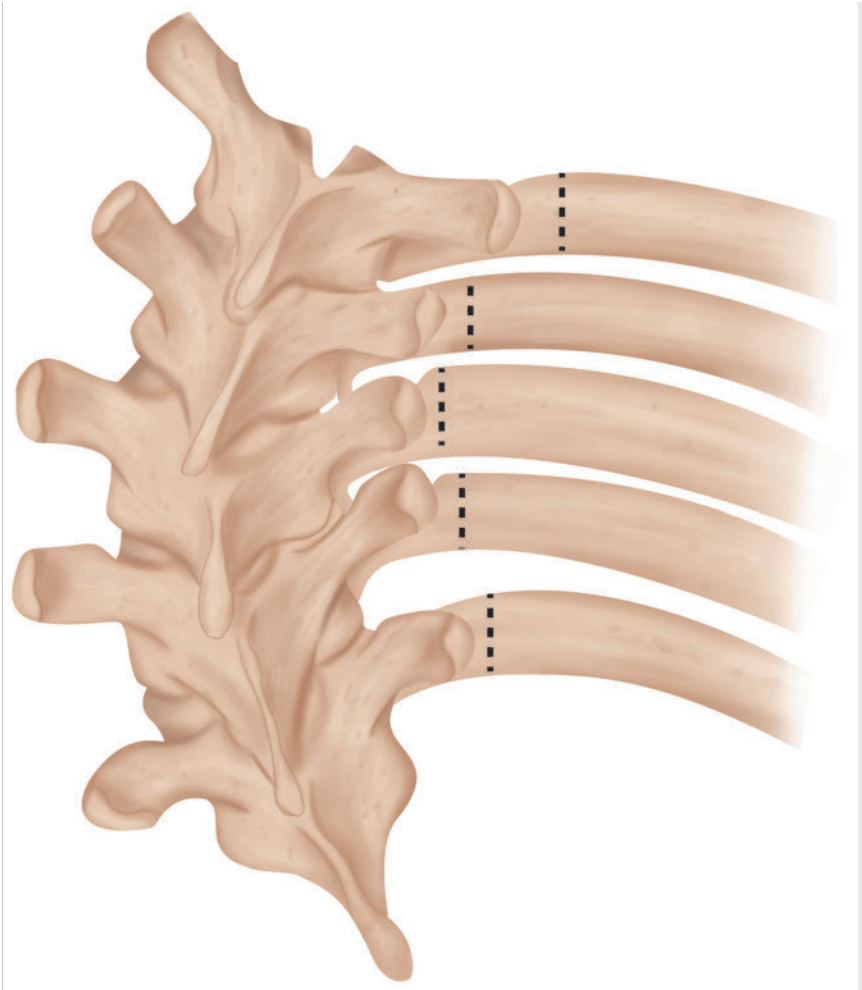

Fig. 63.1 Deformed spine showing rib osteotomy.

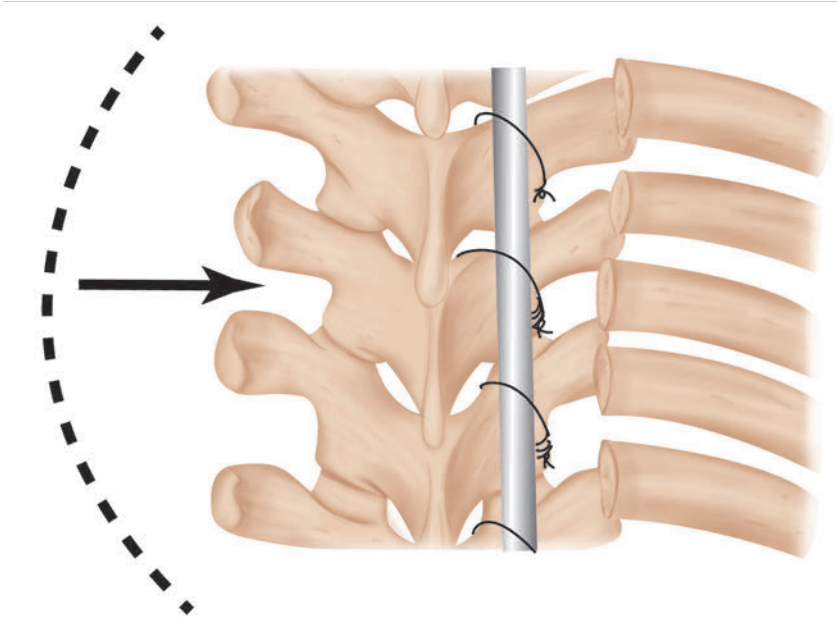

Fig. 63.2 Corrected deformity with instrumentation.

63.8 Tips, Pearls, and Lessons Learned

Rib synostosis, particularly in a congenital curve, makes dissection difficult. Comprehensive preoperative radiographic evaluation helps avoid surprises. Always obtain a postoperative chest radiograph to search for a hemothorax or pneumothorax.

63.9 Difficulties Encountered

If a pneumothorax is suspected either intraoperatively or postoperatively, tube thoracostomy should be performed.

63.10 Key Procedural Steps

Standard posterior exposure to the tips of the transverse processes from the caudal to the cephalic level of the spine under consideration for fusion is performed (See **Video 63.1**). The sequence for a routine posterior instrumented fusion is the following: place the pedicle screws, perform the facetectomies, prepare sites and place hooks, perform laminotomies for sublaminar wire placement, perform the thoracoplasty, and then consider the concave rib osteotomies.

Exposure is then carried lateral to the tips of the transverse process of the vertebrae under consideration. The dissection proceeds in a plane directly over the ribs for 2 to 3 cm. The paraspinal muscles give comparatively little resistance, given the surgeon is on the concave side of the curve. Subperiosteal dissection of the rib is performed as in a standard thoracotomy approach using the Alexander and Doyen instruments. A rib cutter is used to perform the rib osteotomy (▶ Fig. 63.1). The area is filled with saline, and positive ventilation provided by the anesthesiologist is used to check for air leaks. A chest tube is placed immediately if an air leak is found. During the correction maneuver the rib lateral to the osteotomy should be elevated above the medial portion of the rib, transverse processes, or spinal instrumentation, as the spine is corrected in the direction of the rib osteotomy sites (▶ Fig. 63.2).

63.11 Bailout, Rescue, and Salvage Procedures

If the pleural cavity is entered during the procedure, a chest tube should be placed. Draping wide will facilitate this if tube placement is necessary.

Pitfalls

- Unrecognized pneumothorax
- Anterior displacement of the lateral portion of the rib into the chest cavity

64 Thoracoplasty: Anterior, Posterior

Luke Madigan

64.1 Description

Thoracoplasty is a technique used to alleviate the cosmetic rib deformity associated with scoliosis by way of rib resection.

64.2 Key Principles

Rib deformities are encountered with advanced curves in both congenital and adolescent idiopathic scoliosis. They can also be encountered as a consequence of previous posterior fusions. Patients often present with coronal sitting imbalance and cosmetic concerns.

64.3 Expectations

Improvement of overall truncal appearance

64.4 Indications

Rib deformity is a commonly encountered problem in patients with adolescent idiopathic scoliosis or congenital scoliosis with or without previous surgery. Rotation of the rib on the convex side of the curve gives a prominent hump that is sometimes not improved with curve correction. It can be seen with previously fused patients who have developed crank-shaft deformities. Patients typically present with coronal sitting imbalance and cosmetic concerns. Indications for thoracoplasty include:

- To correct sitting imbalance secondary to rib hump
- To balance shoulder height
- Worsening rib hump
- Cosmetically unacceptable deformity

64.5 Contraindications

- Skeletal immaturity
- Patients with pre-existing pulmonary compromise
- Patients whose pulmonary status would be compromised due to resection of numerous ribs, detachment of the diaphragm, detachment of accessory respiratory muscles, or poor chest cage compliance

64.6 Special Considerations

To prevent recurrence, delay thoracoplasty until the patient is physiologically mature.

64.7 Special Instructions, Positioning, and Anesthesia

There are three generally accepted techniques for rib resection thoracoplasty: (1) open posterior, (2) open anterior transthoracic, and (3) endoscopic internal transthoracic. Each technique has its advantages and disadvantages depending on the clinical circumstances. As with all deformity surgery, each case should be individualized based on patient and curve characteristics.

64.7.1 Open Posterior (Single Midline Incision or Midline with Posterior Axillary Line Incisions)

- Prone position
- Drape field from one anterior axillary line to the opposite one

Fig. 64.1 Operative positioning.

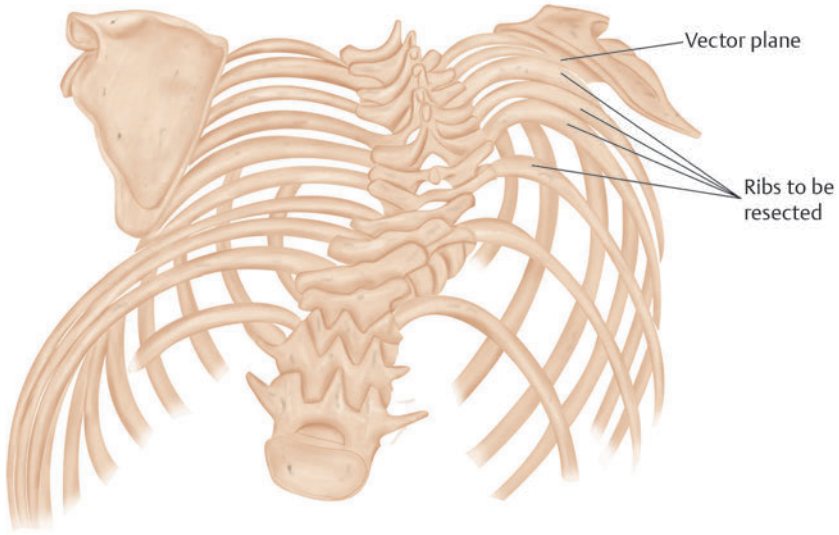

Fig. 64.2 Axial view of cosmetic rib deformity associated with scoliosis.

64.7.2 Open Anterior Transthoracic Internal

- Double-lumen endotracheal tube
- Lateral position
- Drape arm free to determine intraoperative scapular position or possible postthoracoplasty impingement (▶ Fig. 64.1)
- Drape from midline posteriorly to the sternum anteriorly

64.7.3 Endoscopic Transthoracic Internal

- Double-lumen endotracheal tube
- Lateral position
- Drape arm free to determine intraoperative scapular position or possible postthoracoplasty impingement (▶ Fig. 64.1)
- Drape from midline posteriorly to the sternum anteriorly

64.8 Tips, Pearls, and Lessons Learned

- Make sure to trim the rib flush with the transverse process at each level to avoid scapular impingement with shoulder motion.
- Thoracotomy instruments should be readily available during endoscopic procedures in case open emergency exposure is needed.

64.9 Difficulties Encountered

- To estimate correction required and the potential need for thoracoplasty, certain characteristics must be elucidated prior to surgery. The flexibility of the structural and compensatory curve, the sagittal and coronal balance, as well as the shoulder heights and the extent of scapular winging, must be taken into account when postprocedure thoracoplasty is planned. By evaluating these parameters it allows the surgeon to determine if the spine or both the spine and the ribs need to be addressed to gain good correction.
- Three-dimensional computed tomographic reconstructions can be used to estimate the locations and extent of resection that is needed to attain good correction. The resected amount will allow the scapula to descend into the resection bed that is created, thereby decreasing the deformity (▶ Fig. 64.2).
- Pulmonary function testing is advised to assess single lung ventilation in the setting of open thoracotomy or endoscopic resection.

64.10 Key Procedural Steps

64.10.1 Open Posterior Approach: Single Midline Incision

- Midline incision over the surgical levels
- Bluntly raise the trapezius, rhomboids, and serratus anterior as a single layer of muscle
- Peel the paraspinal muscles from their lateral margins toward the midline over the ribs to be resected
- Strip the ribs by cauterizing the surface and then use a rib stripper or Cobb elevator around the circumference of the rib.
- Be careful to protect the neurovascular bundle located underneath the inferior edge of each rib
- Mark the resection margins
- Osteotomize with a sagittal saw with soft tissue protector
- Contour the osteotomy with a bur in the coronal plane to give a smooth chest contour

64.10.2 Open Posterior Approach: Two Incisions

- Parallel and paramedian incisions
- Dissection is similar to the single midline technique.
- Distal aspect of the rib is exposed by raising a latissimus dorsi flap from lateral to medial.
- The rib is osteotomized through both incisions.

64.10.3 Open Anterior Approach

- Expose the chest via thoracotomy.
- Perform any necessary procedures first.
- Mark margins for resections from outside-in with 18-gauge needles
- With electrocautery, raise the pleura over each rib and complete the subperiosteal dissection.
- Contour the osteotomy with a bur in the coronal plane to give a smooth chest contour.

64.10.4 Endoscopic Approach

- Create three portals in a triangular configuration with the apex just lateral to the nipple line.
- Perform any associated procedures first.
- Mark margins for resections from outside-in with 18-gauge needles.
- With electrocautery, raise the pleura over each rib and complete the subperiosteal dissection with a endoscopic, angled Cobb elevator.
- Grasp the rib at the distal osteotomy site and complete the dissection by pulling forward and then create the proximal osteotomy and remove the rib.

64.11 Bailout, Rescue, and Salvage Procedures

Having intimate knowledge of the three techniques of thoracoplasty will allow the surgeon to tailor the surgical approach to the patient's pathology.

Pitfalls

- Delay thoracoplasty until the patient is physiologically mature to avoid recurrence.

65 Posterior Spinal Anchor Strategy Placement and Rod Reduction Techniques: Vertebral Column Resection versus Direct Vertebral Column Rotation

Lawrence G. Lenke and Fernando E. Silva

65.1 Description

Deformity correction by posterior instrumentation using vertebral column resection versus direct vertebral column rotation is described.

65.2 Key Principles

Vertebral column resection and three-dimensional direct vertebral column rotation permits correction of coronal, sagittal, and axial plane deformities. These advanced techniques, the latter in particular, allow chest wall derotation and a superior true apical derotation maneuver using pedicle screws constructs. They permit correction of all curve types in the Lenke classification.

65.3 Expectations

Both techniques are employed using pedicle screw constructs. With direct vertebral column rotation, a vertebral column manipulation device is used. Both of these advanced deformity correction maneuvers are undertaken posteriorly, and should lead to leveled shoulders and a balanced spine.

65.4 Indications

Direct vertebral rotation is particularly useful when fusing to L3 in the treatment of thoracolumbar/lumbar adolescent idiopathic scoliosis, Lenke 1–3C and 6C. It can also be selectively applied to isolated thoracic, thoracolumbar, and lumbar curves. Vertebral column resection provides balanced correction of large magnitude, stiff/fused kyphoscoliotic spines.

65.5 Contraindications

With curves other than Lenke 1A(-) and 1A(N), a 90-degree counterclockwise rod-rotation maneuver should not be undertaken, especially with curves that are at risk for decompensation with full rod rotation maneuvers. Lenke 5C curves are a relative contraindication, as an anterior approach might be preferred to help obviate adjacent segmental focal kyphosis. These curves can still be approached posteriorly as long as particular attention is paid to the preservation of the proximal end ligaments and soft tissues.

65.6 Special Considerations

Upright lateral radiographs are required to demonstrate mild lordosis or hypokyphosis in the thoracic profile (T5–T12). Selective fusion should always be undertaken if possible, especially when addressing Lenke 1–3C and 6C curves. In the latter, apical derotation in all three planes coupled with in situ translatory loads and selective compression/distraction, can lead to an excellent spinal/shoulder balance.

65.7 Special Instructions, Positioning, and Anesthesia

The patient is placed prone on a Jackson frame or appropriate four-poster frame, ensuring adequate lumbar lordosis. The arms are placed in the 90–90-degree position. Neurologic monitoring equipment, with or without the Stagnara wake-up test, is deemed appropriate.

65.8 Tips, Pearls, and Lessons Learned

65.8.1 Instrumentation

When using free-hand, fluoroscopic-assisted, or image-guided placement of pedicle screws, each level should be instrumented in the same sequential manner. It is imperative to clearly expose the bony anatomy (pars, superior articular process, and transverse process), as a guide to safe and consistent placement of pedicle screw instrumentation. When employing a Lenke probe, no forceful attempts should be made while cannulating the pedicle. The probe is particularly designed to enter the pedicle with a twisting and gentle pushing motion. If palpation of the prepped screw path does not feel right, do not place a screw. Free-hand screw placement should not be attempted in an apical concavity fusion mass, especially in the absence of bony landmarks.

65.8.2 Vertebral Column Resection

- Remove the transverse process before removing the rib head, as anatomically the latter becomes more accessible.
- The lamina above and below, as well as the epidural fat at the level where the vertebral column resection is performed, must be removed to ensure no compromise of the thecal sac/neural elements during correction.
- The final posterior closure should not exceed 3 cm.
- The initial attempt at closure should only accomplish 50% of the initial intended deformity closure (1.5 cm), and be well controlled.
- At the distal end of the construct, reduction screws are placed, particularly in very kyphotic cases, to facilitate initial cantilever reduction.

65.8.3 Direct Vertebral Rotation Employing Vertebral Column Manipulation Device

- A single multiaxial reduction screw (MARS) is placed in the concavity at the apical vertebra to help seat the rod and allow a translatory moment to "pull" the apex into the prebent rod.

65.8.4 Correction Maneuvers

- Open closed disks; conversely, close opened disks
- To create kyphosis, distract away the apex at the concavity; we prefer translational loads to a prebent rod.
- To create lordosis, compress towards the apex in the convexity.
- Leave appropriate tilt the lowest instrumented vertebra (LIV), based on Lenke's lumbar modifier.
- Use initial angle created by a line between the screws at the LIV, prior to correction, and a horizontal-to-gauge final tilt placed on the LIV.

65.9 Difficulties Encountered

Correction maneuvers might prove difficult when addressing stiff curves and may lead to bone-implant failure; however, with these advanced techniques, the loads are shared by the multiplicity of the pedicle screw instrumentation used. Pedicle screws can be safely placed even in very small pedicles; in this situation, we advocate using peripedicular screw placement into the vertebral body. Hence, this controlled load sharing allows for correction of large and stiff curves via both techniques.

65.10 Key Procedural Steps

65.10.1 Vertebral Column Resection (► Fig. 65.1; Video 65.1)

Following exposure of the appropriate proximal and distal preoperatively selected levels and placement of segmental pedicle screw instrumentation, the transverse processes of the selected vertebral resection are removed. This is followed by the removal of 3 to 5 cm of the medial rib. The rib heads are disarticulated bilaterally from their ligamentous attachment to the vertebral body and saved as a structural autograft to be placed over the defect after the vertebral column resection is completed. Bilateral laminectomies are carried out from the pedicles above where the vertebral column resection is performed, to the pedicles below. The pedicles at the resection level are skeletonized bilaterally. After neuromonitoring testing of the roots at the level where the vertebral column resection is undertaken, the roots are ligated and preganglionically sacrificed, if necessary. The lateral pedicle–vertebral body wall junction is subperiosteally dissected toward the anterior surface of the vertebral body and the segmental vessels are then held laterally with the help of malleable retractors. A large portion of the lateral pedicle–vertebral body wall junction is then removed and decancellation of the vertebral body is completed. This is performed bilaterally, but not simultaneously. While being performed on one side, a temporary rod must secure the vertebral column, and then transferred to the other side while the decancellation is undertaken contralaterally. This provisional fixation is imperative to prevent any unnecessary translation or catastrophic neural element compromise. The adjacent upper and lower disks are then removed. The anterior vertebral body wall is thinned down, but not completely resected to serve two purposes: protect the anterior vessels and provide a surface for further arthrodesis. The posterior vertebral body wall is then carefully dissected off the ventral aspect of the dura and fractured in a gentle, controlled fashion, anteriorly with the aid of a reverse angle curette. The entire ventral surface of the thecal sac is then completely decompressed. The initial correction maneuver is controlled compression on the convexity of the scoliosis being corrected, or simultaneously from both sides if kyphosis is being corrected. Hence, it must be ensured that at no time are the neural elements lengthened, as this is a shortening procedure. Direct visualization of the thecal sac must be ensured to ascertain no unnecessary compression of the neural elements. At this point, an appropriately sized anterior cage is placed to serve as both support and as a fulcrum for axis of rotation to complete the closure. Appropriate forces are placed on the coronal plane to correct any residual deformity, and appropriate compression/distraction maneuvers are performed. Arthrodesis is then carried out in the usual manner, while also securing the halved rib graft over the posterior defect.

65.10.2 Direct Vertebral Rotation Employing Vertebral Column Manipulation Device (► Fig. 65.2)

Upon complete exposure of the spine and segmental placement of pedicle screws, a correcting rod is bent into the appropriate sagittal plane alignment and placed in the concavity of the deformity. This rod is then captured, but not locked, proximally with set screws. The vertebral column manipulator (VCM) device is assembled by attaching derotator implant holders to the convex and concave apical pedicle screws. These initial derotator implant holders are then connected to the derotator bridges. Derotator bridge handles are applied and in this manner; the construct is quadrangulated. An apical derotation maneuver is performed with the VCM, while rotating the correcting rod into the appropriate sagittal plane profile. When this is completed, there should be an adequate correction of the thoracolumbar rib hump. At this point, while holding the correction/derotation with the VCM, the distal end of the correcting rod is then captured with reduction screws and set plugs are placed. Once all set plugs are tightened and the initial correction is obtained, the VCM device is quickly removed and coronal benders are used for the necessary in situ coronal correction. The holding rod is then contoured into the appropriate sagittal plane and tightened into the pedicle screws with set plugs. Appropriate shoulder balance is obtained by selective distraction/compression moments at the top of the construct. Compression forces are performed toward the apex of the convexity to correct hyperkyphosis in the thoracic region and/or increase lordosis in the lumbar region. The latter maneuver

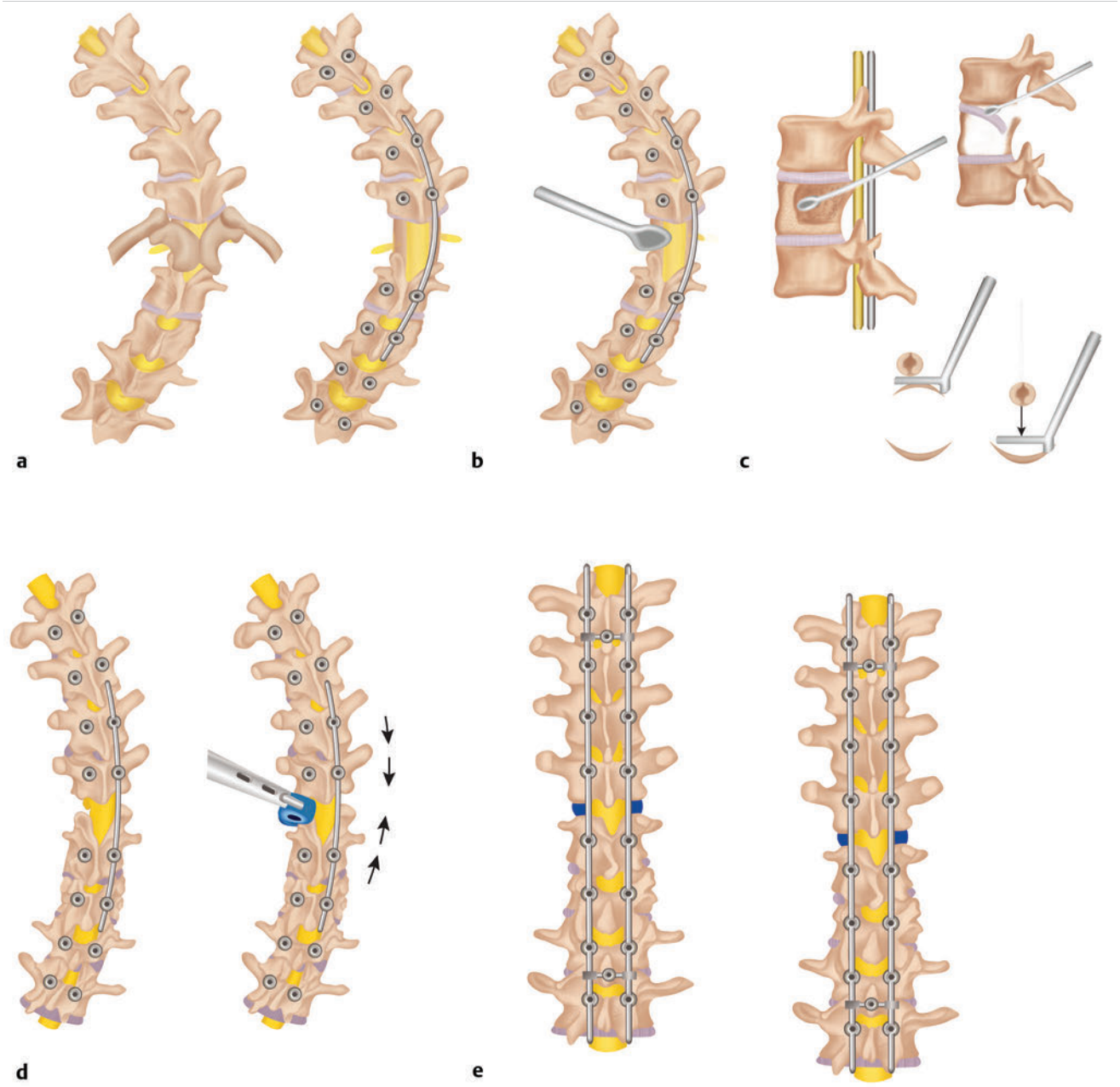

Fig. 65.1 Exposure and degree of bony resection. (**a**) Pedicle screws and temporary rod placement. (**b**) Anterior vertebral body exposure and resection. **(c)** Diskectomies and posterior vertebral body removal. (**d**) Initial compression and cage placement. (**e**) Final correction and rib graft arthrodesis.

further helps to obviate any flatback issues in the lumbar spine. Although distraction at the concavity increases kyphosis and reduces lordosis, we prefer placing an appropriate sagittal bend in the rod and using translation moments for such corrections so as to avoid distraction injuries to the neural elements. The LIV is then appropriately compressed/distracted, leaving a tilt angle based on the degree of rotation (Lenke's lumbar modifier) to prevent coronal imbalance, especially in selective fusions. The cephalad construct is revisited and further compression/distraction maneuvers are performed to fine-tune shoulder balance and to optimize the LIV angle.

65.11 Bailout, Rescue, and Salvage Procedures

Any changes in motor-evoked potential or somatosensory potential immediately require checking the leads, making sure the irrigation used is of the appropriate temperature and increasing the blood pressure to no less than 75 mm Hg, as well as checking all implant sites for loosening the instrumentation. If necessary, the instrumentation must be removed and the patient returned to the operating room at a later date to complete the operative intervention.

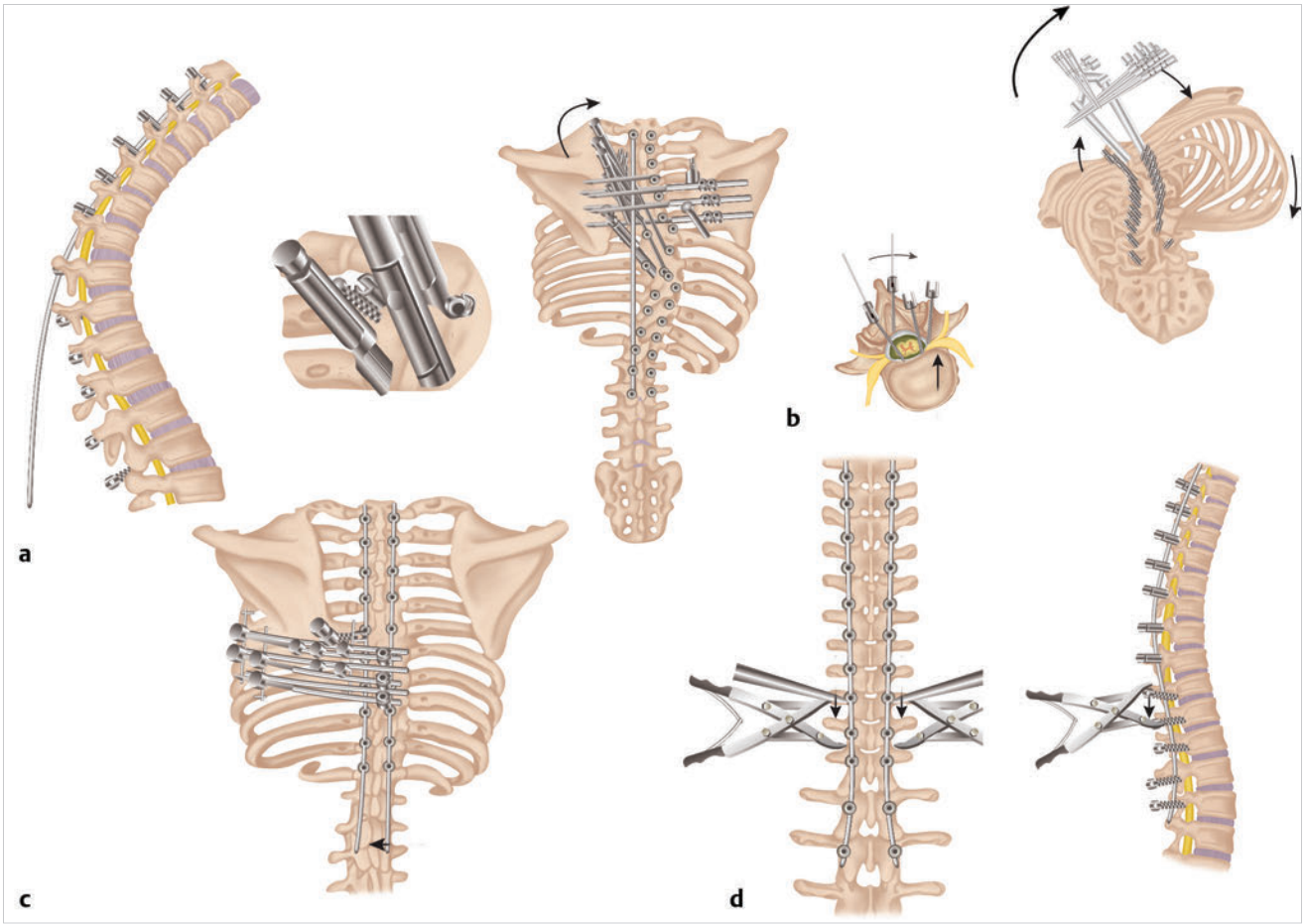

Fig. 65.2 (**a**) Initial correcting rod placement. Note use of apical multiaxial reduction screw and distal reduction screws. (**b**) Assembled direct vertebral column rotation (DVR) system and mechanics of triplanar correction. (**c**) Placement of holding rod. (**d**) Final correction loads via selective compression/distraction.

Pitfalls

- Difficulties are often encountered with curves greater than 100 degrees
- Failing to recognize proximal thoracic kyphosis
- Decompensation if failure to instrument to the appropriate LIV and leaving the correct amount of LIV tilt to optimize spinal balance.

66 Anterior Spinal Anchor Strategy for Deformity: Placement and Rod Reduction Techniques

Rafael A. Buerba, Michael C. Fu, Keith H. Bridwell, and Jonathan N. Grauer

66.1 Description

A surgical technique for two-screw/two-rod constructs for thoracolumbar/lumbar scoliosis is described.

66.2 Key Principles

This procedure is used to correct the coronal plane deformity while preserving or enhancing lumbar lordosis.

66.3 Expectations

The goal with such constructs is to correct coronal and sagittal deformity with the rod and vertebral rotation with the screws. Lordosis can be optimized with anterior structural support (bone grafts or interbody cages). The stability afforded by two rod constructs allows for early return to activities.

The primary advantage of anterior over posterior surgery is shorter constructs. Although this may be challenged with current posterior screw/rod constructs, anterior deformity correction and stabilization is appropriately considered in certain cases.

66.4 Indications

Such constructs are considered for adolescent thoracolumbar/lumbar curves. As with posterior deformity indications, surgery is considered in cases where the Cobb measurement is greater than 45 degrees. Particularly large curves (over 70 degrees), however, are generally not able to be addressed with anterior-only constructs.

66.5 Contraindications

- Thoracic curves (negative impact on pulmonary functions)
- Curves that do not at least correct to 40 degrees or better on flexibility maneuvers
- Most curves over 70 degrees
- Osteoporosis
- Severe sagittal plane malalignment

66.6 Special Considerations

Bicortical screw fixation is considered essential as this creates a very strong triangular grip on the vertebral body that allows the application of powerful corrective forces during derotation.

66.7 Special Instructions, Positioning, and Anesthesia

Standard general anesthesia is used with the patient in a lateral decubitus position. The convex side is up; the concave side is down. Correction of thoracolumbar and lumbar curves using a thoracoabdominal approach does not have a negative impact on pulmonary functions. If the spine is exposed below T9, it is not necessary to deflate a lung.

As with other deformity procedures, neuromonitoring is generally used. Anesthesia compatible with this is thus necessary.

66.8 Tips, Pearls, and Lessons Learned

Diskectomy should be performed all the way to the posterior longitudinal ligament, and the cartilage end plates should be removed to the bone end plates. Disk spreaders and chisels are helpful. The opposite outer fibers of the anulus on the concave side may act as a hinge during the deformity correction and may prevent overcorrection of the deformity; thus, we generally do not recommend complete resection of them. In stiff thoracic curves, however, it may be necessary to resect the entire anulus to the opposite side. Fluoroscopy can be helpful to assess the extent of the diskectomy.

66.9 Difficulties Encountered

For fairly large curves, it may be somewhat difficult to reach the top and bottom. There may be a tendency with the anterior screw, both proximally and distally, to inadvertently put it into the adjacent disk space. Also, it is helpful to take a rib at least one level, if not two levels, higher than the intended proximal vertebra. If the anterior fusion extends up to T11, it is best to take the 9th rib rather than the 10th rib. Disadvantages of this procedure include some trauma to diaphragm and a longer ileus.

66.10 Key Procedural Steps

The procedure for a thoracolumbar curve is described here through a thoracoabdominal approach. Typically, this is a left lumbar curve. The patient is placed in the lateral decubitus position: right side down, left side up. A curvilinear incision is made paralleling the 10th rib. The latissimus dorsi and external oblique muscles are incised down to the 10th rib. This rib is then subperiosteally stripped, exposed, and resected. The chest is then entered through the bed of the 10th rib. The retroperitoneum is then entered through the cartilage of the 10th rib.

Peritoneum is swept off the undersurface of the deep abdominal muscles, which are then taken down parallel to the skin incision. The peritoneum is then swept off the undersurface of the diaphragm, which is taken down with a 1.5-cm peripheral radial cuff. Next, the segmental vessels are ligated at midbody level from T12–L3. Exposure of the vertebral bodies is then accomplished from the base of the pedicle around to the other side. Note that the psoas muscle needs to be mobilized

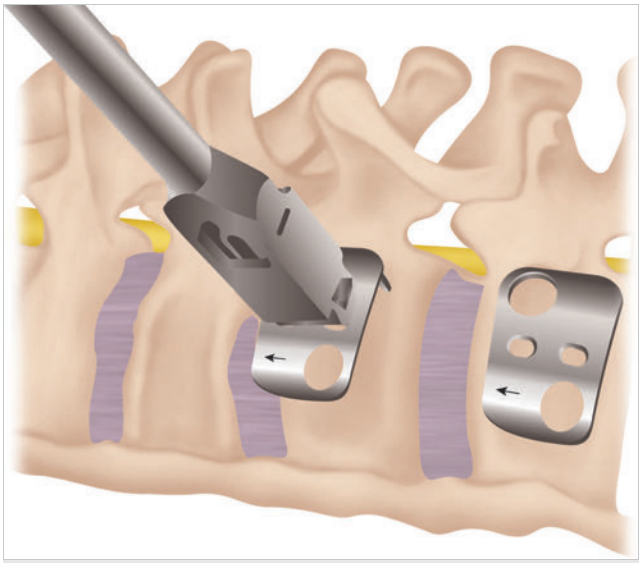

Fig. 66.1 Application of staple to vertebral body. The gray areas between the vertebral bodies represent the area of intervertebral disk resection.

back to the depression of the intervertebral foramen; otherwise, the staples will not be able to be placed posteriorly enough. Care should also be taken to not injure any segmental vessels on the opposite side.

Next, diskectomies are performed as described previously. It is very helpful to use disk distractors to facilitate getting to the concave anterior corner. The staples are then placed (**Video 66.1**). It is important that each staple be centrally placed (▶ Fig. 66.1). This is to optimize placement of the staple itself as well as to facilitate appropriate trajectory of the screws.

In placing the screws through the staples (▶ Fig. 66.2), the surgeon needs to visualize the posterior margin of the disk space to be absolutely sure the screws are being safely directed. The surgeon will be leaning his hand back further on the more apical segments than the end segments. The staples and screws will appear to sit more posteriorly at the apical segments than the end segments, but in fact they are all equidistant from the base of the pedicle. Blunt-tipped screws are generally used, and the contralateral cortex should be penetrated approximately 2 mm to ensure secure engagement. After placing the staples and screws, it is helpful to verify under fluoroscopy that the screws are all placed correctly and that they are bicortical.

Next, 1-cm sections of rib graft should be inserted into the anterior concave area of the disk space. Some surgeons prefer to insert appropriate-sized cages. The intended effect of either is that their insertion in the anterior concave portion of the disk spaces will help preserve the lumbar lordosis as well as aid in the correction of the deformity during derotation.

The next step is to accomplish direct derotation through the anterior vertebral body screws. To accomplish this, first contour, cut, and engage the anterior rod with the aligned screw heads (▶ Fig. 66.3). Place the caps on each screw once the rod is in the desired position to secure it.

Once the anterior rod is secure and all the caps are in place, grasp it with a pair of rod holders and rotate it for correction (▶ Fig. 66.4). To maintain the derotated position, the screws adjacent to the apex should be temporarily tightened. As rod

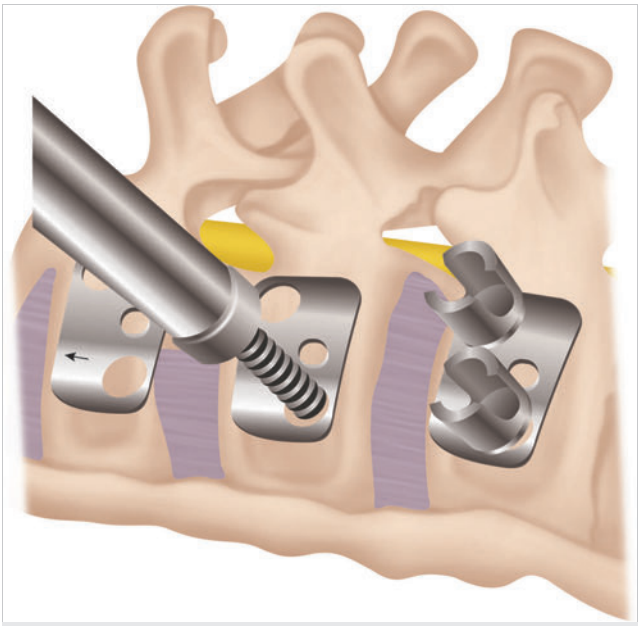

Fig. 66.2 Screw insertion through staple. It is imperative that the screws are directed anteriorly and away from the posterior longitudinal ligament. The gray areas between the vertebral bodies represent the area of intervertebral disk resection.

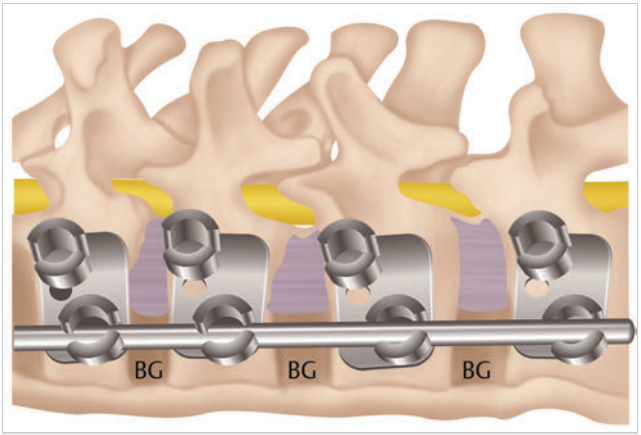

Fig. 66.3 Anterior rod introduction. BG: bone graft or interbody cage (based on surgeon preference). The dark areas between the vertebral bodies represent the area of intervertebral disk resection.

rotation progresses, the apical vertebra is derotated, simultaneously reducing the kyphosis. Once derotation is accomplished, the remaining vertebrae are compressed sequentially starting with the interior screws and working out toward the end vertebrae screws. If necessary, the anterior rod can be bent in situ once the screw heads have been tightened.

Before inserting the posterior rod, the rest of the bone graft is packed into the residual disk spaces and gently impacted. The posterior rod is then introduced in the same manner as the anterior rod (▶ Fig. 66.5). If the desired deformity correction has not been achieved by the tightening of the anterior rod screws, then the set screws at the ends of the anterior rod can be released. Once this occurs, the tightening and compression of the end screws of the posterior rod should be performed.

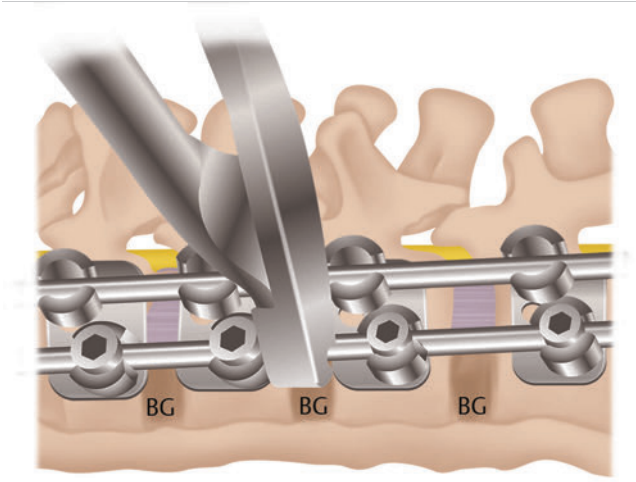

Fig. 66.4 Anterior rod rotation. BG: bone graft or interbody cage (based on surgeon preference). The dark areas between the vertebral bodies represent the area of intervertebral disk resection.

Once the lordosis is satisfactory, the set screws on the anterior rod can be retightened. If done in this manner, the tightening of the posterior rod will both correct the scoliosis and produce more lordosis. In other words, the posterior rod can be thought of as the stabilizing rod and the anterior rod as the correcting rod.

66.11 Bailout, Rescue, and Salvage Procedures

If screw purchase is deemed not adequate or if the screws pull out during correction, the appropriate salvage is a posterior instrumented fusion, preferably with pedicle screw implants.

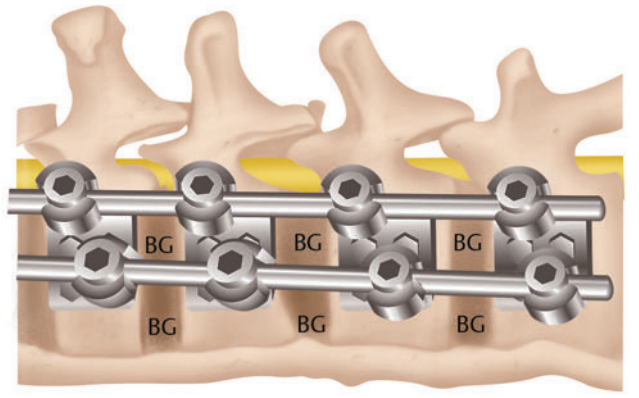

Fig. 66.5 Completed posterior rod contouring and placement. BG: bone graft.

This is not likely to occur if the procedure is performed on a patient under the age of 30. It is usually possible and feasible to instrument to L4. It is often not feasible to instrument anteriorly below L4 because the vena cava and bifurcation is often in the way at L5.

Pitfalls

- It is important that all screws be bicortical. It is absolutely critical that the screw tips be directed away from the canal and the foramen. At times, it is possible to reach around the front with a gloved finger to feel the tip of the screw. If this is not possible, another option is to put the screw in and then take it out and palpate with a sounder to feel whether the screw is bicortical.
- It is also critical to not reduce segmental lordosis.

67 Fixation Strategies and Rod Reduction Strategies for Sagittal Plane Deformities

Kirkham B. Wood

67.1 Description

To safely and effectively stabilize the hyperkyphotic thoracic or thoracolumbar spine with bilateral rigid posterior segmental instrumentation while reducing the sagittal curvature into a more physiologic range is the goal described.

67.2 Key Principles

By securing the longitudinal members (rods) proximally or distally into multiple hook or pedicle screw anchors, careful and judicious cantilever reduction is used to deliver the rods into increasingly distal sites of fixation and hyperkyphosis is reduced.

67.3 Expectations

Modern instrumentation systems with their multiple sites of fixation and increased rigidity over those from previous eras allow not only improved construct rigidity and a higher rate of fusion, but also an ability to safely and consistently correct hyperkyphosis toward a more physiologic sagittal contour and to maintain that correction over time.

67.4 Indications

Thoracic or thoracolumbar hyperkyphosis

67.5 Contraindications

- Pre-existing fusion of the anterior column
- Tumor or infection
- Some congenital kyphosis
- Absent posterior elements
- Severe osteoporosis

67.6 Special Considerations

Hooks (pedicle, transverse process, or laminar) were historically the principal means of fixation. Although the transverse processes of the upper thoracic spine are potential sites of hook fixation, those of T10–T12 are frequently insufficient for adequate purchase, dictating the use of either pedicle screws or in certain cases, sublaminar wiring or synthetic band fixation. Pedicle screws have become increasingly recommended, however, as anchors due principally to their increased pullout strength. They may be used in all levels; nevertheless, the risk of a pedicle breach or neurologic injury should always be considered.

67.7 Special Instructions, Positioning, and Anesthesia

The patient is positioned prone on a four-poster frame (Jackson table) or with transverse rolls under the chest and pelvis. The operating table may be flexed slightly initially in severe cases, so that returning to the horizontal position aids in the reduction maneuver.

67.8 Tips, Pearls, and Lessons Learned

Individuals with long-standing spinal deformity are often more osteopenic than control populations; thus, undue force should not be used to avoid fracture of the laminae or transverse processes if hooks are used. Pedicle screw fixation is strongly recommended in these situations.

Because of the risk of proximal or distal fixation cutout during the reduction maneuver, especially in the elderly, wires or tapes can be passed around and or through the spinous processes or the laminae, further securing the instrumentation. Additionally, a supra- or an infralaminar hook at the ends of the construct may help protect against pullout of the distal pedicle screws.

Posterior fusion alone typically works well, but in kyphosis surgery, the incidence of pseudarthrosis is greatly affected by the degree of deformity. Hence, curves over 70 to 75 degrees may require a concomitant anterior fusion, especially in the setting of insufficient posterior elements. Alternatively, even in more severe or rigid curves all posterior pedicle screw constructs can certainly be used, but many will augment the autologous bone grafting with various forms of synthetic fusion extenders.

Because of altered anatomy, intraoperative lateral radiographs, C-arm imaging, or newer operating room computed tomography- (CT-) guided navigation systems may be recommended to aid in the successful placement of the pedicle screws.

Currently, many pedicle screw systems have extended connectors that allow, first, the capture of the rods to the screws, and then the gentle and gradual final reduction of the rods to the base of the screw.

Historically, to lessen the chances of kyphotic angulation at the distal junction of the instrumentation (DJK), it was recommended to try to include not only the whole Cobb angle measurement of the kyphotic curve, but include the first lordotic space as well. Despite this, there have been certain instances of DJK, especially with midthoracic curvatures with large lumbar compensatory lumbar lordosis. Current recommendations are to extend the instrumentation distally to include the vertebra bisected by a vertical drawn cephalad from the posterior superior corner of S1 (▶ Fig. 67.1).

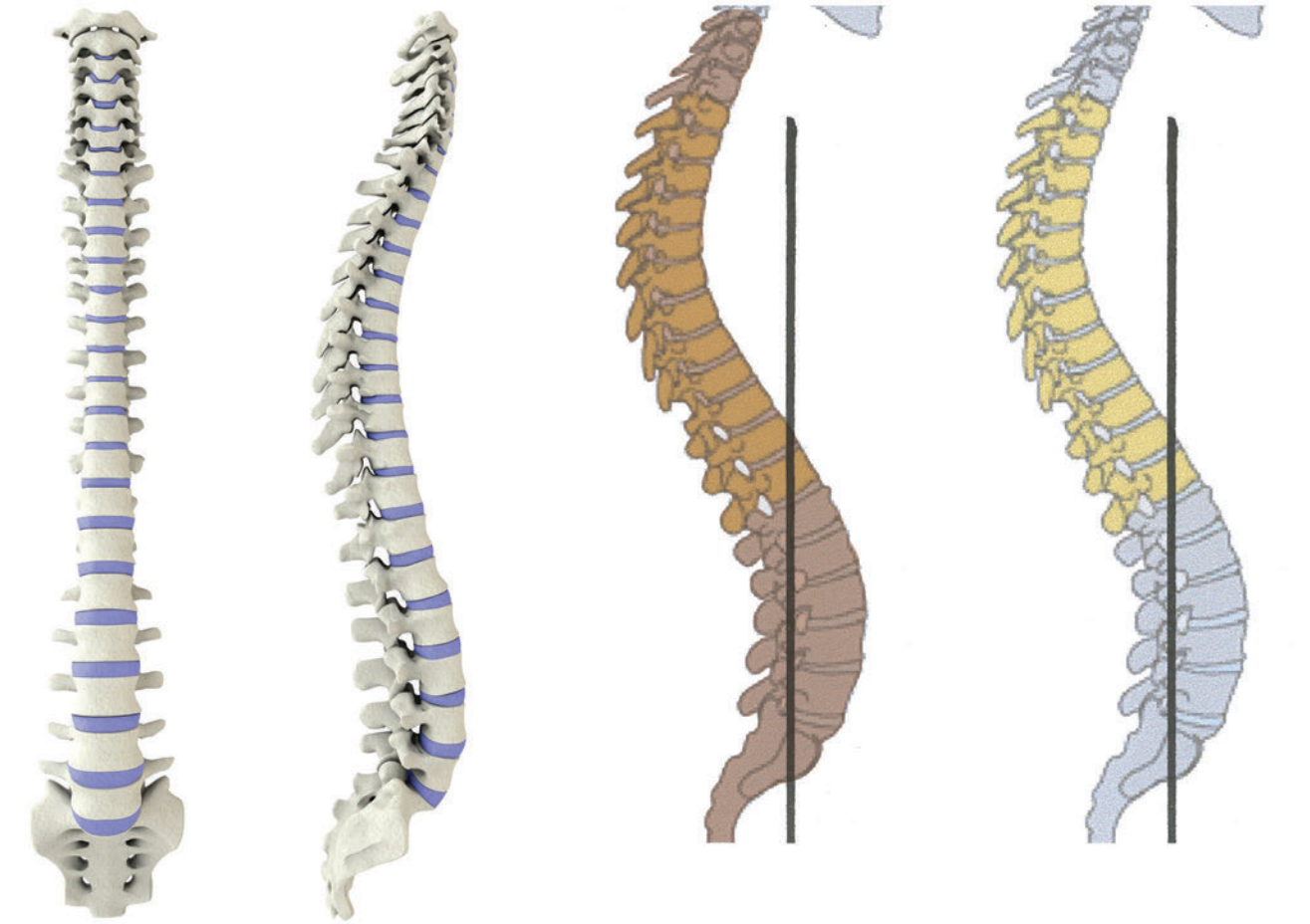

Fig. 67.1 A vertical line drawn superiorly should cross the most caudally vertebra instrumented.

Care must be taken when performing any reduction technique involving shorter segment fixation situations such as thoracolumbar fractures. Often, after reducing the malalignment from the posterior approach, a significant "gap" may exist anteriorly from a deficient ventral column. A secondary anterior procedure may be indicated to restore the anterior column's structural integrity.

67.9 Difficulties Encountered

The major complication following the reduction of thoracic kyphosis is the development of a junctional kyphosis beyond the levels of instrumentation. Reasons for this include failing to include all kyphotic vertebrae proximally, as well as distally, including the first lumbar segment, or failing to reach the posterior superior vertical sacral line. Overcorrection of the kyphosis (>60%) is also associated with an increased risk of proximal deformity. Careful preoperative hyperextension radiographs over a bolster will help define the spine's rigidity and suggested expected degrees of correction. Age, osteopenia, and previous spine surgery should also be taken into consideration during the reduction maneuver as far as correction expectations are concerned.

67.10 Key Procedural Steps

In cases of thoracic kyphosis (e.g., Scheuermann's), the levels of posterior fusion and instrumentation should include at least the entire kyphosis as measured by the Cobb method to include the first lordotic disk—often T12–L1—and preferably a vertebra also bisected by the vertical sacral line (▶ Fig. 67.1). The basic instrumentation construct consists of a minimum of three to four pedicle screws (or hook claw constructs) on both sides above the apex of the kyphosis and similarly distally. Two ¼-inch rods are bent to represent the desired end kyphosis, and then introduced first into the most proximal or distal anchors, and secured. Then, by careful cantilever reduction, the rods are sequentially introduced into the remaining fixation points (▶ Fig. 67.2). Finally, segmental compression toward the apex of the kyphosis is applied. Alternatively, on each side, two rods can be cantilevered towards each other and then linked with multiple connectors (▶ Fig. 67.3). These two techniques can be viewed in **Video 67.1**.

In cases of thoracolumbar kyphosis (e.g., fracture) depending on the osseous quality, pedicle screws with or without supporting laminar hooks can be placed one or two levels above and below the pathology. With advancing osteopenia, more levels should be included both proximally and distally.

67.11 Bailout, Rescue, and Salvage Procedures

The use of postoperative external immobilization can help protect those at risk of either bone or instrument failure. External bone growth stimulation can also aid in potentially speeding up the fusion process, further protecting against either fusion or instrumentation failure.

Pitfalls

- Use of sublaminar wires or bands as a sole means of fixation can cut through the bone
- Hook or screw dislodgment
- Laminar or transverse process fracture
- Prominent instrumentation in the thin individual

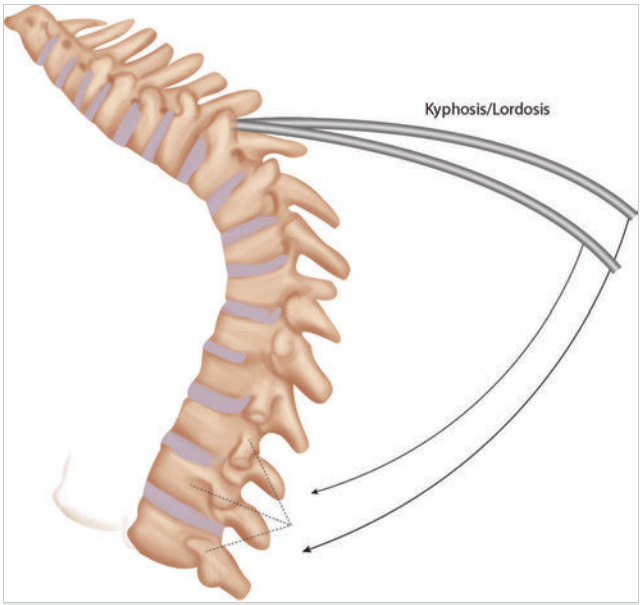

Fig. 67.2 After securing the rods proximally into the clawed anchors, the underbent rod is gently introduced and fixed into more caudal segments, correcting the hyperkyphosis.

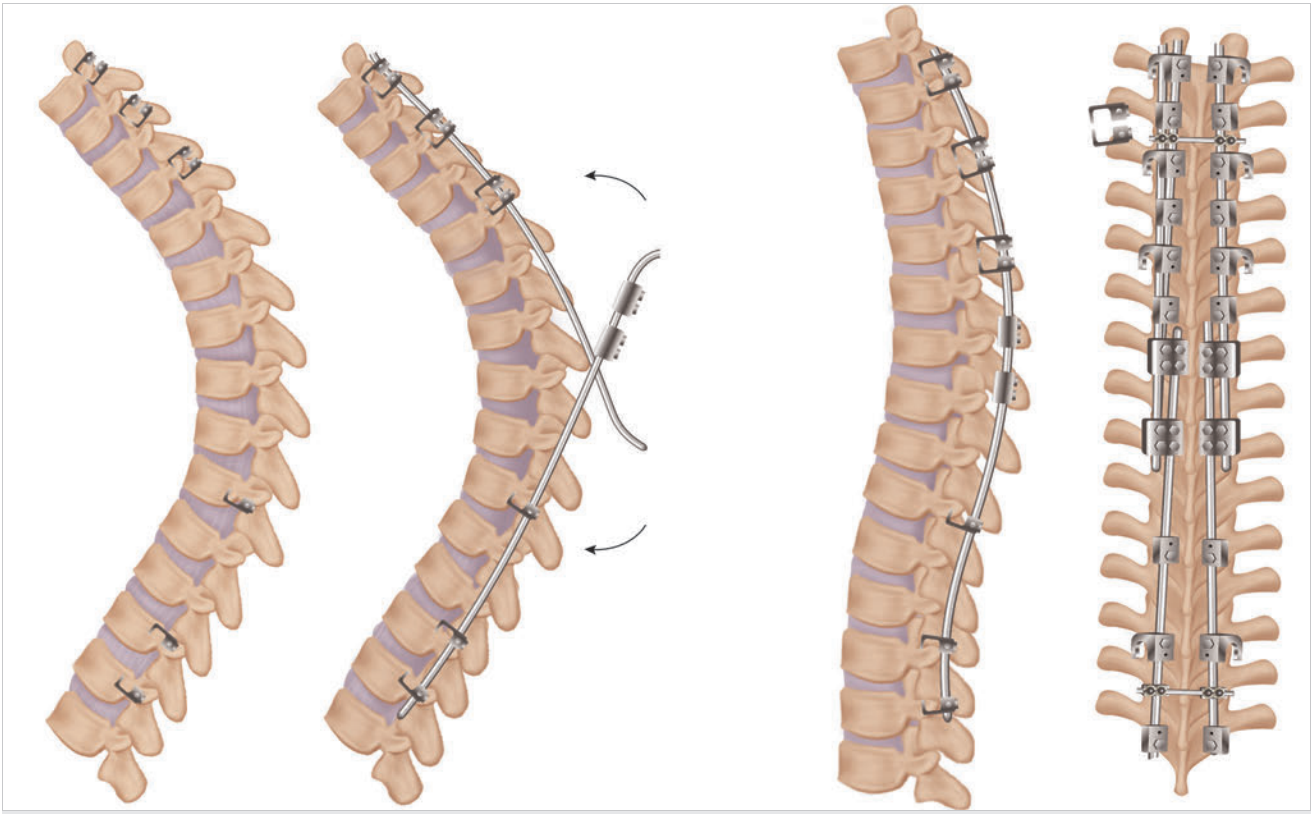

Fig. 67.3 Two rods on either side can be levered towards each other (a) and connected to gently (b) reduce the kyphosis from two directions.

68 Vertebral Column Resection

Priyanka Kumar, Paul W. Millhouse, Caleb Behrend, and Alexander R. Vaccaro

68.1 Description

Severe rigid spinal deformity is a difficult problem for the spine surgeon (▶ Fig. 68.1). Vertebral column resection (VCR) is a recognized means of achieving significant spinal alignment correction in the setting of a rigid deformity as this technique enables correction of a multiplanar deformity. Although VCR has traditionally been utilized for congenital spinal deformities, tumor resection, and spondyloptosis, more recently the technique has been used to treat severe rigid spinal deformities.

68.2 Key Principles

Vertebral column resection refers to the complete resection of the posterior elements, including the pedicles, and the entire vertebral body. The procedure is also considered a vertebral column *shortening* procedure. This can be achieved through an anteroposterior "circumferential" approach (staged or same-day), or through a posterior-only approach. Vertebral column resection does not typically result in direct bone-on-bone contact, as is common with Smith-Petersen (SPO) and pedicle subtraction osteotomies (PSO); therefore, reconstruction of the anterior spinal column is required. A thoracic anterior approach may result in compromised pulmonary function, and thus may push the surgeon to perform a posterior-only VCR if patients do not have sufficient cardiac or pulmonary reserve function to tolerate the procedure. However, the posterior-only procedure is more technically challenging and should only be attempted by the highly skilled deformity surgeon. Mastery of an anteroposterior VCR is necessary prior to attempting a posterior-only VCR. It is important to note that VCR procedures generally involve long operating times with significant blood loss. Larger resections are associated with increased blood loss and higher risk of neurologic deficits, as well as other significant complications.

68.3 Indications

Vertebral column resection is indicated for severe fixed deformities including:

- A fused anterior and posterior spinal column after a previous fusion or in the setting of a congenital scoliosis (fixed multiplanar deformity)
- A fixed and rigid spinal kyphosis or kyphoscoliosis (especially for thoracic deformity)
- Severe coronal and sagittal imbalance
- Spondyloptosis
- Spinal tumors

Sagittal plane decompensation is often a leading cause of patient complaints in the setting of deformity. However, patients may also have complaints related to coronal plane deformity including difficulty standing or sitting secondary to pelvic obliquity with imbalance, apparent leg-length discrepancy, as well as cosmetic concerns. Less commonly, patients will have cardiopulmonary compromise related to the deformity. After consideration of the patients' overall health, goals of treatment, and comprehensive evaluation of the spinal deformity, a draft of the surgical approach, technique (i.e., multiple Smith-Petersen osteotomies, pedicle subtraction osteotomy [PSO], or vertebral column resection), levels of resection, and levels of instrumentation is made.

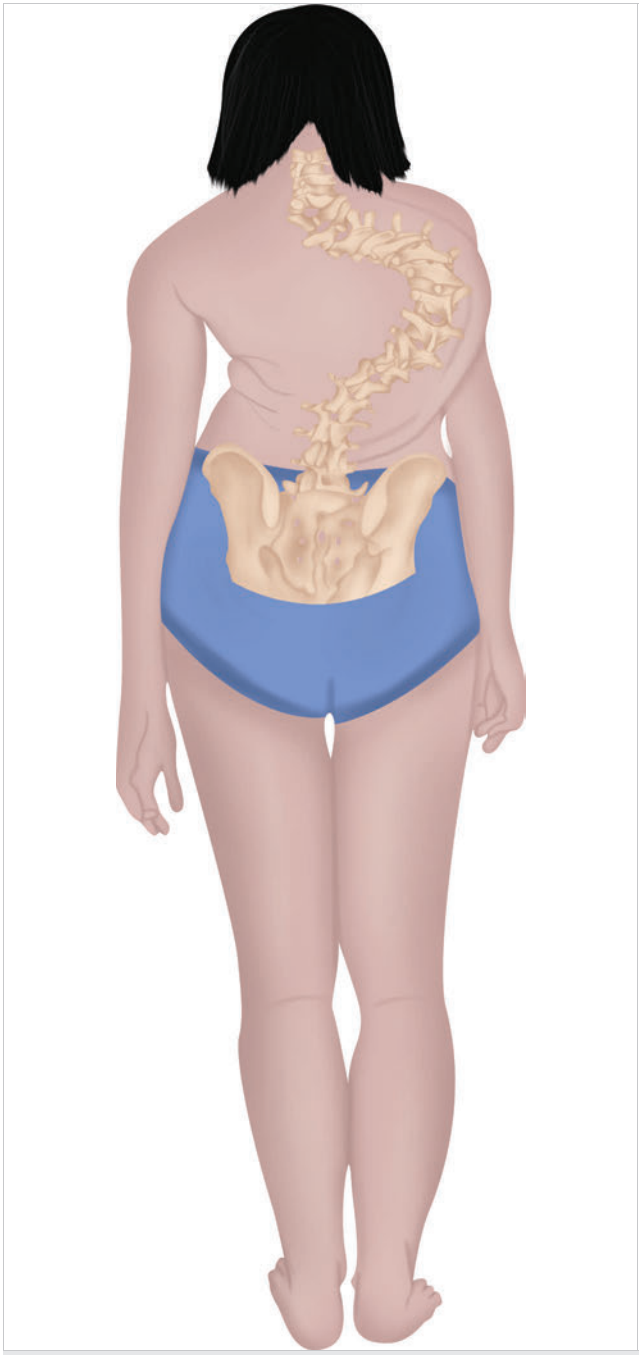

Fig. 68.1 A posterior view of a severe coronal plane deformity.

68.4 Contraindications

A VCR is not recommended for medically compromised patients who cannot undergo extended periods of anesthesia or potentially significant blood loss. As with most other procedures, spinal instrumentation is generally contraindicated in the case of active infection. Additionally, respiratory dysfunction and circulatory dysfunction are relative contraindications, as they may not allow patients to tolerate a VCR. The nature of the deformity may also contraindicate VCR. For instance, pedicle dysplasia, involving widespread segments of the spine, may prevent necessary screw insertion and spinal stability during the procedure.

68.5 Special Considerations

A thorough understanding of the complexity of the multiplanar deformity is obtained from the physical exam and complete radiograph series. This must include standing anteroposterior (AP), lateral, and side-bending films. In some cases push prone, supine AP, fulcrum bending, traction, or supine hyperextension crosstable lateral films may also aid in planning. This series assists the surgeon in assessing the potential flexibility of the deformity, as well as the overall sagittal and coronal decompensation. If known leg length discrepancy is present this may be corrected for with a block under that foot. If standing images are unobtainable, then sitting AP and lateral radiographs should be obtained. Further radiographic evaluation may include a thin-section computed tomography (CT) scan with sagittal, coronal, and three-dimensional (3D) reconstruction. The CT scan provides detailed information on the bony anatomy allowing for examination of postsurgical changes, congenital anomalies, morphology of the pedicles, vertebral rotation, translation, listhesis, and segmental symmetry.

Magnetic resonance imaging (MRI) is helpful for evaluating associated neural axis abnormalities and associated stenosis and can guide preoperative planning for decompression. It also shows the relative position of the vascular structures, the presence of cysts, pseudomeningoceles, and irregularity in the posterior elements.

The segmental blood supply can also be quite tenuous, especially in revision or congenital scoliosis surgery. Thus, it is generally advisable to avoid ligating these arteries, if at all possible. As an alternative, the artery should be temporarily clipped and only ligated if there are no motor evoked potential (MEP) monitoring changes after waiting several minutes.

68.6 Special Instructions, Positioning, and Anesthesia

For anteroposterior vertebral column resection, the patient is placed in the lateral decubitus position on a radiolucent table. Typically, the right lateral decubitus (left-side approach) is employed using a beanbag with an axillary roll. Following the anterolateral portion of the procedure, the patient is flipped to the prone position on an open Jackson frame. For a posterior-only VCR, the patient is placed directly in the prone position on a well-padded radiolucent table. The arms are placed with the shoulders abducted 90 degrees and the elbows flexed 90 degrees, and in such a way that imaging may be obtained if needed. The abdomen should be decompressed as much as possible and all bony prominences well padded. The neck is placed in a neutral to slightly flexed position.

68.7 Tips, Pearls, and Lessons Learned

The goal is to achieve a balanced correction without stretching or compressing the spinal cord. Generally, only one or two vertebrae require resection along with the associated disks (three disks for two-level resection), especially for sharply angulated deformities. This is determined by the magnitude of the deformity and the acuteness of the angulation. For long, sweeping rigid curves, additional vertebrae may need to be resected.

Anticipating large blood loss, all efforts should be made to control bleeding from the procedure onset. This includes meticulous dissection and control of soft tissue bleeding with liberal use of powdered thrombin-soaked Gelfoam (Pfizer Pharmaceuticals), or similar available commercial products such as FloSeal (Baxter Healthcare). The use of tranexamic acid, bipolar hemostatic sealers, and red blood cell recycling technology may also be considered. For tumor resections, consideration should be given to preoperative arterial embolization; however, this may also increase the risk of spinal cord compromise or loss of function secondary to the embolization. In addition, blood pressure should be maintained at the resting mean arterial pressure during correction, watching closely for any acute drops. Spinal cord neuromonitoring, specifically somatosensory evoked potentials and MEPs, should also be used judiciously

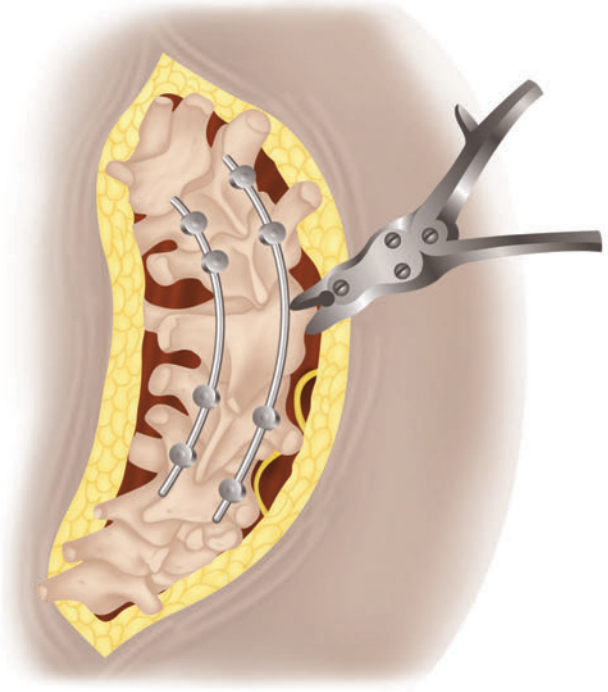

Fig. 68.2 Once the spinal anchors (screws) are placed posteriorly, the posterior vertebral resection is commenced.

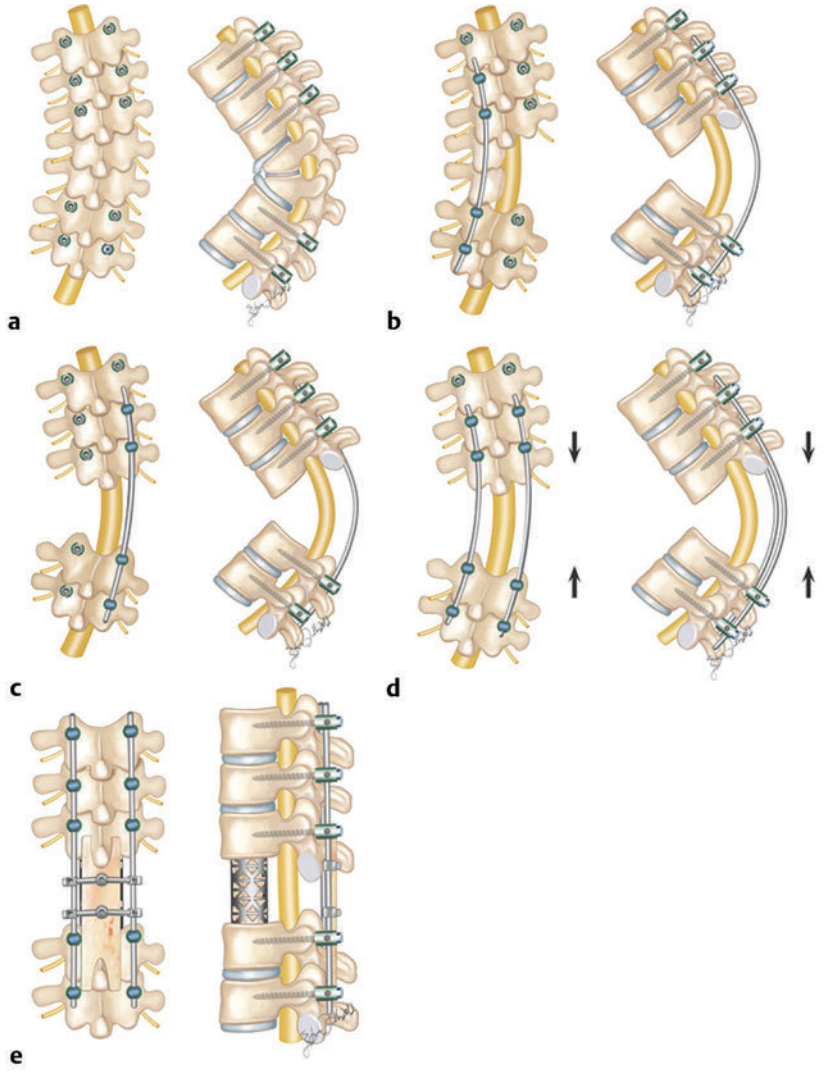

Fig. 68.3 Stepwise illustration of the posterior-only vertebral column resection (PVCR). (**a**) Pedicle screws are inserted above and below the levels to be resected. **(b)** After temporary fixation with a rod on one side, the disk and bony elements are removed contralaterally. **(c)** The resection procedure is carried out on the other side after the rod is switched. **(d)** The deformity correction is effected gradually by bending the rods in situ. (**e**) Anterior column support is provided with a polymer or metallic cage or allograph strut graft. Anterior column support is secured via posterior spinal instrumentation compression. *(Reproduced from Enercan M, Ozturk C, Kahraman S, et al. Osteotomies/ spinal column resections in adult deformity. Eur Spine J. 2013; 22 Supp 2:S254–S264)*

throughout correction. After the procedure a wake-up test, involving close coordination with the anesthesia team, may also be considered.

68.8 Difficulties Encountered

A critical difficulty that may be encountered is compromised neurologic function during or after VCR. Consequently, complete visualization and slow steady correction are essential to performing the procedure safely. Additionally, because VCR is an inherently destabilizing procedure, rigid internal fixation with at least two or three levels of fixation both proximal and distal to the level of resection is typically required. The condition of the bone should be considered because compromised bone quality or osteoporosis may necessitate additional levels of fixation. Pseudarthrosis and instrumentation failure are significant concerns as well. Persistent imbalance or loss of lumbar lordosis may also be encountered during the correctional procedure.

Small pedicles, which make pedicle screw fixation problematic, may be difficult to identify preoperatively, and alternative fixation strategies should be considered at these levels if it is believed to be a critical level of fixation.

68.9 Key Procedural Steps

68.9.1 Anteroposterior (Circumferential) Vertebral Column Resection

The anterior procedure is accomplished through either a thoracotomy or thoracoabdominal approach on the convex side of the deformity. If there is a solid fusion, an anterior osteotomy is indicated. Ideally, an osteoperiosteal flap is elevated, but this is often impractical. Often, the vertebral segments to be resected are removed down to the level of the adjacent disk, which is also removed with the articular cartilage of the adjacent end plate, to expose bleeding subchondral bone. All of the bone back to the posterior longitudinal ligament (PLL) is removed piecemeal. Removing the PLL is optional, as infolding of the PLL into the spinal canal can result in spinal cord compression during

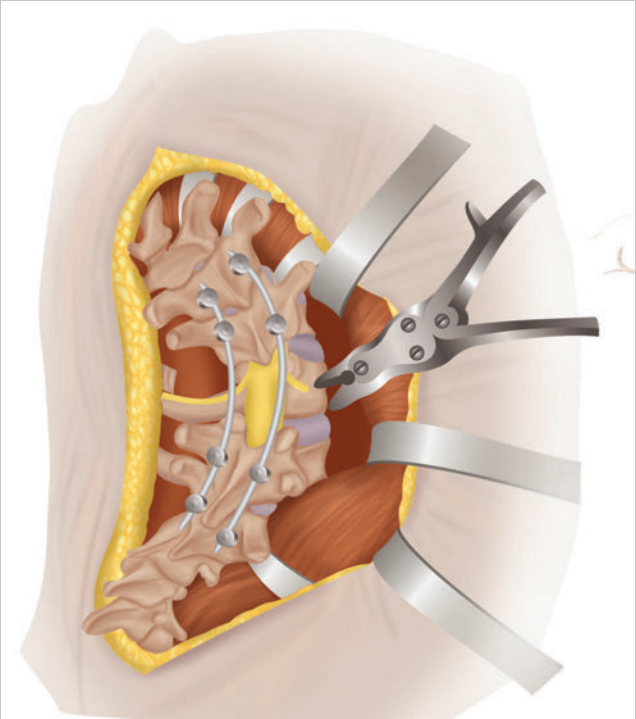

Fig. 68.4 An extracavitary approach allows for simultaneous resection of the anterior and posterior spinal elements. Temporary rods are placed to maintain alignment until the vertebral resection is completed.

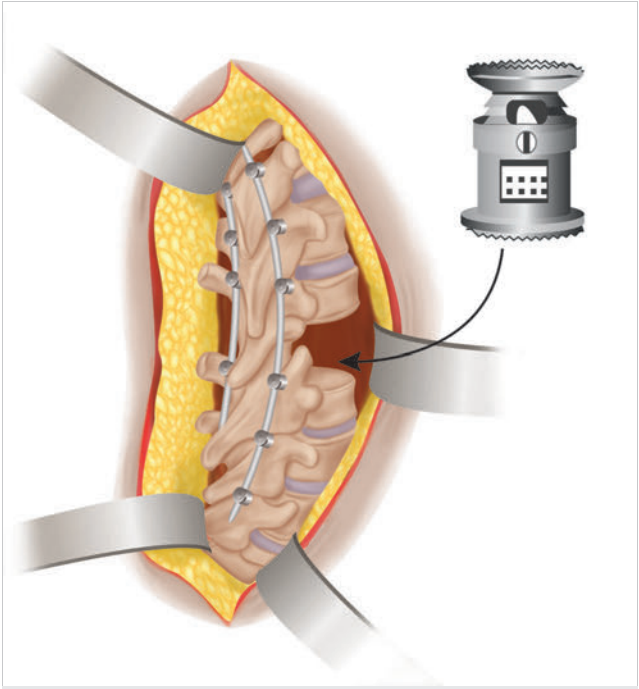

Fig. 68.5 Following the vertebral resection, a cage or spacer is then placed in the anterior column defect as the spine is shortened using the cage as a fulcrum.

correction. The entire vertebral body and convex pedicle are removed. A lamina spreader is helpful to maintain or improve visualization of the area to be resected; however, overdistraction should not be applied. After complete resection, an autologous tricortical iliac crest, femoral allograft, titanium mesh with allograft or autograft, or an expandable cage is placed. A vertebral column shortening will be the outcome, regardless of the chosen interbody spacer. Anterior rod or plate fixation is avoided following grafting to allow for further spinal alignment manipulation during the posterior procedure. The patient is then flipped to the prone position for a posterior element resection and segmental instrumentation, or brought to the operating room at a later date for this procedure (▶ Fig. 68.2).

68.9.2 Posterior-Only Vertebral Column Resection

After complete dissection through a midline incision, segmental bilateral pedicle screw instrumentation is employed at the levels above or below the level of vertebral resection (▶ Fig. 68.3). Posterior VCR is done through the same midline exposure, with an extracavitary approach to the anterior column. This includes complete resection of the transverse processes and associated ribs; more lateral the rib resection allows better visualization of the anterior spinal elements (▶ Fig. 68.4). This is necessary to limit spinal cord retraction, which should be avoided. The thoracic nerves are also resected using suture or hemostatic clips to improve anterior visualization. With progressive resection of the anterior spinal elements a provisional rod should be placed to allow for control of spinal stability with further resection of the vertebral body. A defined strategy must be maintained for hemostasis as vertebral body bleeding can be significant. Packing and hemostatic agents can be used for moderate bleeding with attention turned to the other side if control with these measures is obtained. Often with continued work on the other side, when you return to the beginning side of the surgery, bleeding will be greatly diminished. There is a fine balance between acceptable and unacceptable bleeding. It is important to note that efficiency and continued movement through the procedure is important, but must be balanced with safety. An awareness of the segmental deformity and its proximity to the surrounding vasculature should also be kept in mind during the resection as there is a potential for injury to major vital structures. Resection of the transverse process is followed by removal of the pedicles. When the pedicles are identified, a bur can be used with care to thin the walls of the pedicles, making an intraosseous entry into the vertebral body. With sufficiently thinned pedicle walls, a pituitary can be used to remove the remaining eggshell of bone with care not to injure the spinal cord or create excessive bleeding from the epidural plexus. A large Penfield can be used to protect these structures. The vertebral body is then removed piecemeal with a bur or osteotome. Reverse curettes can be used to tamp bone down from behind the spinal cord into the cavity created by the eggshell procedure. Identification of the disk space and disk resection is performed in a standard fashion with care to use the anterior and opposite anulus to protect the surrounding vital structures. This further defines the cranial and caudal margins of the VCR. After complete resection, autologous tricortical iliac crest, femoral or humeral allograft, titanium mesh cages, or expandable cages are utilized to stabilize the anterior column and serve as a fulcrum for deformity correction. Posteriorly

segmental pedicle screw instrumentation is used for both correction and stabilization of the spine deformity (▶ Fig. 68.5, ▶ Fig. 68.6, ▶ Fig. 68.7). The use of crosslinks should be considered to increase the torsional stability of the construct, which is severely compromised after vertebrectomy.

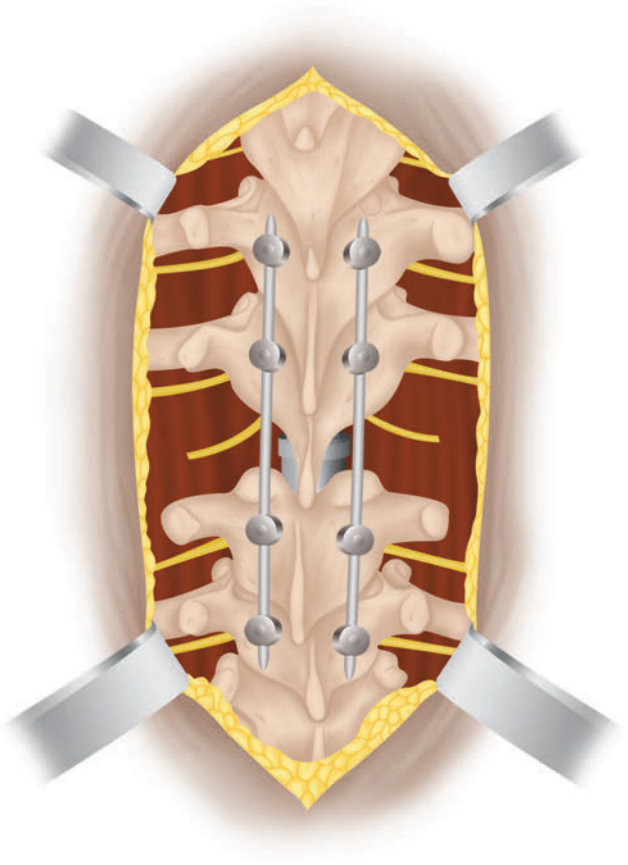

Fig. 68.6 Following anterior and posterior vertebral element resection, the spinal deformity is slowly corrected.

68.10 Bailout, Rescue, and Salvage Procedures

Pedicle screw augmentation techniques, such as cement injection, can be utilized for correction of inadequate fixation. However, these techniques are associated with risks such as cement extravasation through a fractured cortex, thermal damage, difficult removal in the event of infection, and the potential for neurologic compromise.

Additional levels of fixation and cross-links should be utilized in the osteoporotic compromised spine, and if extension to the sacrum is necessary, iliac screw fixation should be used. Postoperative bracing may help limit forward bending and additional pullout forces on posterior instrumentation.

It is highly recommended that intraoperative somatosensory and motor evoked potentials be utilized throughout the procedure to detect potential spinal cord injury. Steroids may be considered in the case of spinal cord injury.

Pitfalls

- Dural tear (most common complication)
- Difficult anterior visualization through a posterior-only approach
- Neurologic compromise
- Pseudarthrosis/loss of fixation
- Iatrogenic deformity
- Uncontrolled bleeding
- Vascular injury

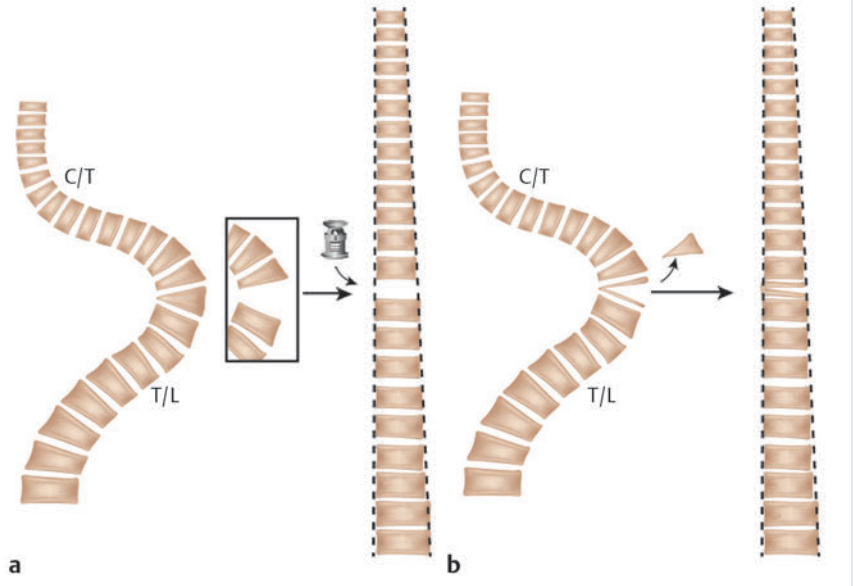

Fig. 68.7 **(a)** A vertebral resection can involve the entire vertebral body or (**b**) involve a wedge resection with incomplete removal of the vertebral body.

69 Posterior Cervicothoracic Osteotomy

Paul Licina and Geoffrey N. Askin

69.1 Description

This extension osteotomy is performed posteriorly at the cervicothoracic junction to correct cervical kyphosis. Although originally described as being performed under local anesthesia with the patient in the seated position, the preferred technique entails general anesthesia, prone positioning, and spinal cord monitoring (**Video 69.1**).

69.2 Expectations

The procedure should improve sagittal balance and restore forward gaze.

69.3 Indications

Severe cervical kyphosis associated with the following:
- Sagittal imbalance
- Loss of forward gaze
- Difficulty eating (jaw opening and swallowing)

Kyphosis severe enough to require corrective osteotomy is usually associated with ankylosing spondylitis or rheumatoid arthritis. Less commonly, kyphosis can result from trauma or cervical laminectomy.

69.4 Contraindications

Severe kyphosis localized to the thoracic spine may be more effectively corrected with thoracic osteotomies. Severe osteoporosis is a relative contraindication.

69.5 Special Considerations, Positioning, and Anesthesia

69.5.1 Level of Osteotomy

The accepted osteotomy level is at C7–T1. This level is sufficiently cephalad for correction of the cervical deformity, while being sufficiently caudad to avoid the vertebral artery in the foramen transversarium. It is also at a level of the spinal canal that is relatively wide.

69.5.2 Head Control

It is best to use a halo ring attached to the bed. It facilitates precise and secure positioning, as well as subsequent head manipulation.

69.5.3 Torso Support

Use of a four-poster frame provides a number of advantages. It can be elevated or otherwise positioned to accommodate the cervicothoracic kyphosis and other associated deformities such as hip fixed flexion deformities. It allows the head to be attached to the bed via the halo ring and provides good access around the head for reduction maneuvers.

69.5.4 Visualization

The required degree of correction is difficult to estimate. The use of transparent plastic drapes allows the surgeon to see the relative position of the head and torso to facilitate visual confirmation of adequate reduction.

69.5.5 Intubation

The flexed position and stiffness of the neck usually poses intubation problems. Preoperative anesthesia assessment includes reviewing lung and cardiac function, and developing an intubation plan. An awake intubation is usually undertaken, using a nasotracheal tube or fiberoptic laryngoscope.

69.5.6 Neurologic Assessment

Spinal cord injury during reduction of the osteotomy, and even during positioning, is a significant risk. For this reason, spinal cord monitoring, ideally both motor and somatosensory, is required with good baseline recordings before the patient is positioned prone.

69.6 Tips, Pearls, and Lessons Learned

69.6.1 Preoperative Planning

The following need to be obtained:
- A lateral photograph to measure the chin–brow angle and to estimate the required degree of correction
- A standing lateral radiograph to assess the desired level and size of osteotomy
- A magnetic resonance imaging (MRI) scan to assess the space for the cord and the vertebral artery anatomy at the proposed site of osteotomy
- A computed tomography (CT) scan to confirm the bony anatomy in the region of the osteotomy

A useful way to gauge the degree of correction required on the lateral X-ray is to trace the spine on tracing paper, cut the paper at the osteotomy level, and then rotate the pieces until sagittal balance has been achieved. The angle between the cut edges then gives the required osteotomy angle (Webb technique).

It may also be helpful to obtain a biomodel (a custom polymer model of the spine based on the CT scan data). The osteotomy and fixation can be planned preoperatively, and the model can be sterilized and used intraoperatively to facilitate three-dimensional visualization.

69.6.2 Control of Osteotomy Reduction

Correction of the osteotomy is often rapid, and precise control may not be possible. Resultant translation can cause spinal cord injury. A way of minimizing this risk is to use a modular cervicothoracic fixation system with cervical lateral mass and thoracic pedicle clamps that allow the rod to slide through them. Once the osteotomy is completed, a temporary malleable rod is inserted and the cervical clamp screws are tightened to secure the rod cephalad to the osteotomy. As the osteotomy is corrected, traction is applied to the caudad end of the rod, allowing it to bend and slide through the thoracic clamps in a controlled fashion, thereby minimizing the risk of translation (Mehdian technique). Newer cervical polyaxial pedicle screws can also be employed, tightening the locking caps in the cervical spine and leaving them loose in the thoracic spine during correction. Transitional rods designed to bridge the cervicothoracic junction are best avoided, as the change in rod diameter at the transition will interfere with rod sliding during correction. Instead, a system with the same diameter rod, but different diameter screws that can be used in the cervical and upper thoracic spine, is the best option.

69.7 Key Procedural Steps

69.7.1 Preparation

The patient is intubated, positioned, and monitored as described above. A long midline approach is made, exposing C3–T4. Imaging is used to confirm the level.

69.7.2 Instrumentation

An instrumentation system that can span the cervicothoracic junction is employed. Lateral mass screws are prepared in C3 or C4–C6, and pedicle screws are prepared in T2–T4 or T5 (▶ Fig. 69.1).

69.7.3 Osteotomy

Using a high-speed bur, the inferior lamina of C6, the whole lamina of C7, and the superior lamina of T1 are removed. The C8 roots are thoroughly decompressed by removing adjacent parts of the C7 and T1 pedicles, and the osteotomy is extended laterally at this level through the C7–T1 facet joints (▶ Fig. 69.2). The dura is often adhered to the lamina, necessitating caution to avoid inadvertent durotomy.

69.7.4 Reduction

If the malleable rod technique is to be used, the rod is inserted and the cervical clamps are tightened to the rod (▶ Fig. 69.3). If not, rods are precontoured to the anticipated degree of correction and fixed to the cervical spine above the osteotomy. One surgeon unscrubs and performs the reduction. The halo ring is detached from the bed, and the surgeon grasps the ring and gently and slowly extends the head, while the other surgeon observes the osteotomy and especially the dura (and guides the malleable rod if this technique is employed). As the reduction approaches completion, the degree of correction is assessed through the transparent drapes. A gap should remain between the C6 and T1 laminae to allow room for the buckled dura (▶ Fig. 69.4).

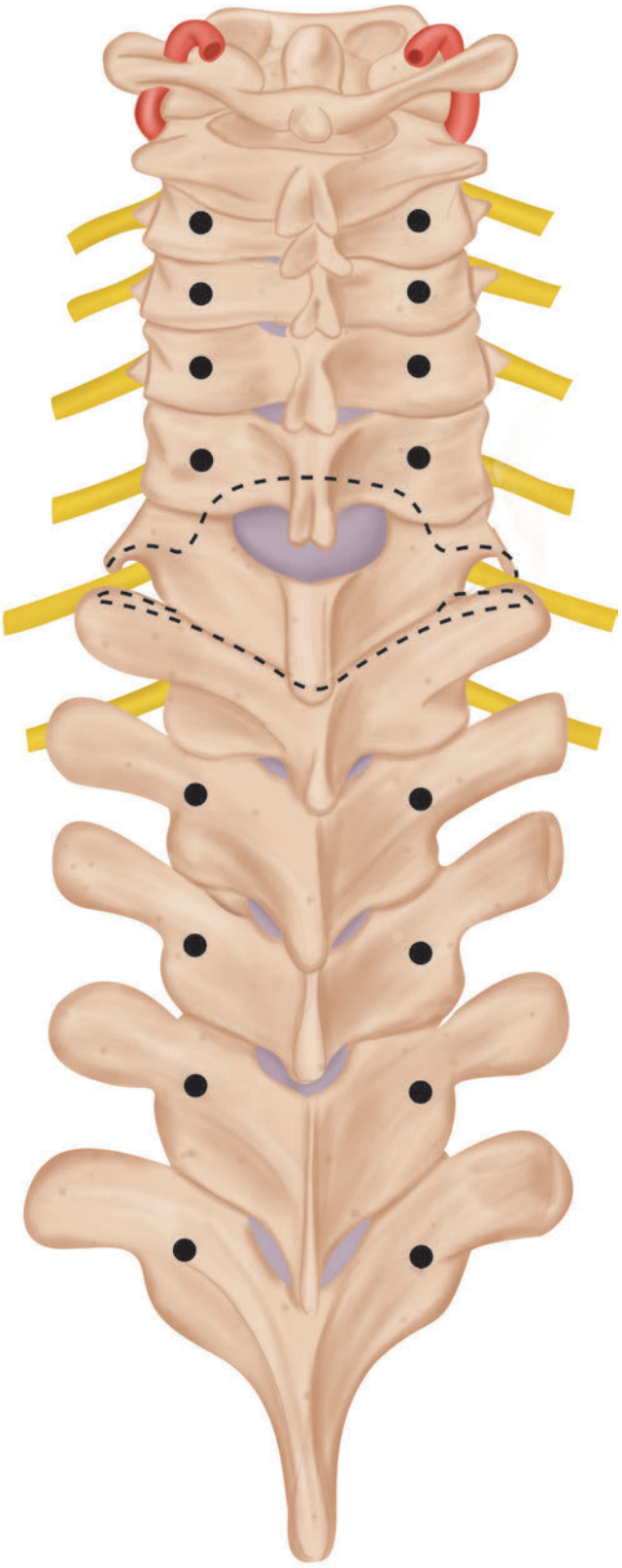

Fig. 69.1 Lateral mass and pedicle screw holes with planned resection.

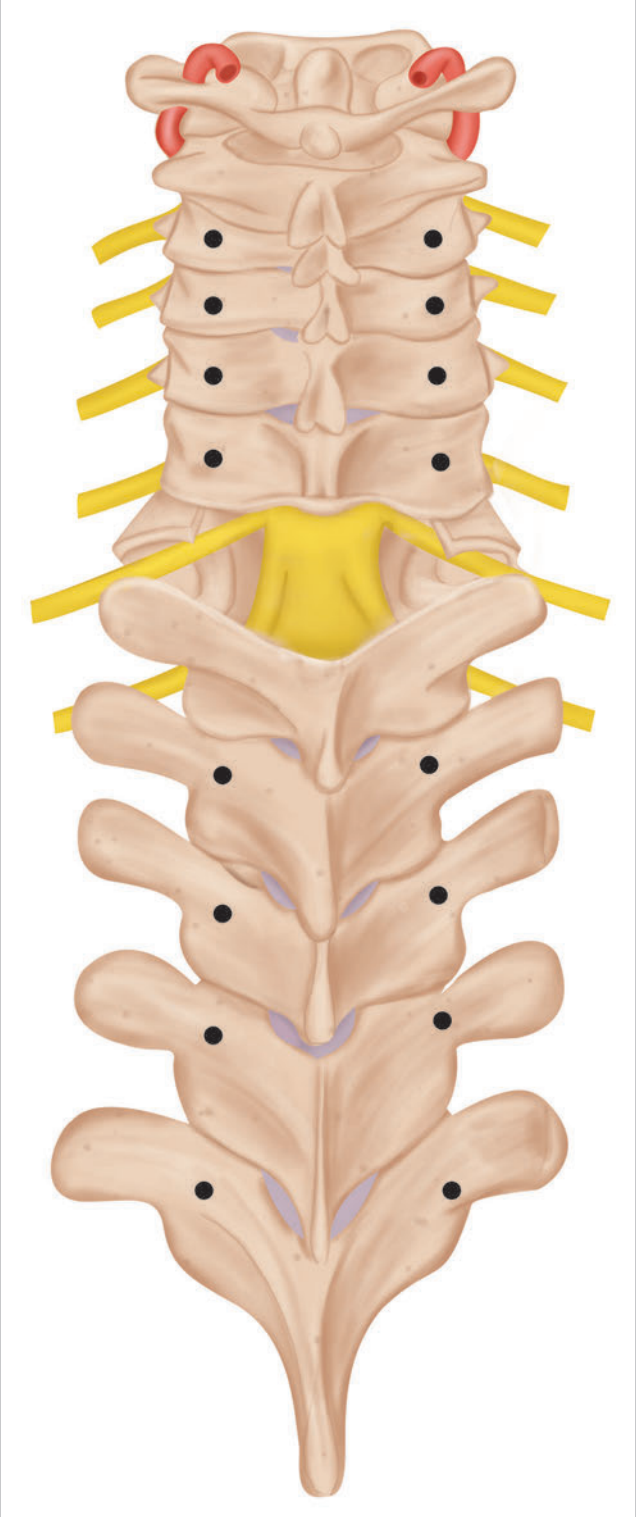

Fig. 69.2 Resection of posterior elements and decompression of C8 roots.

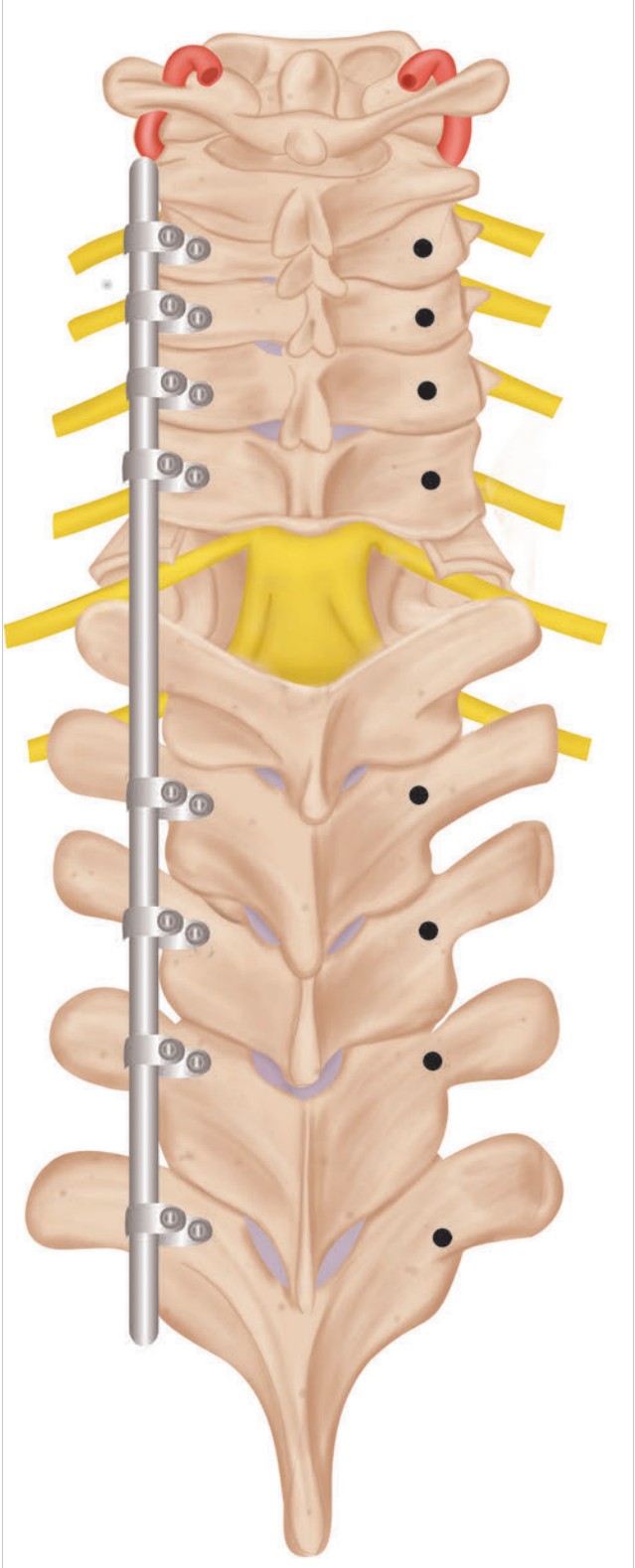

Fig. 69.3 Unilateral insertion of clamps and malleable rod on the left side.

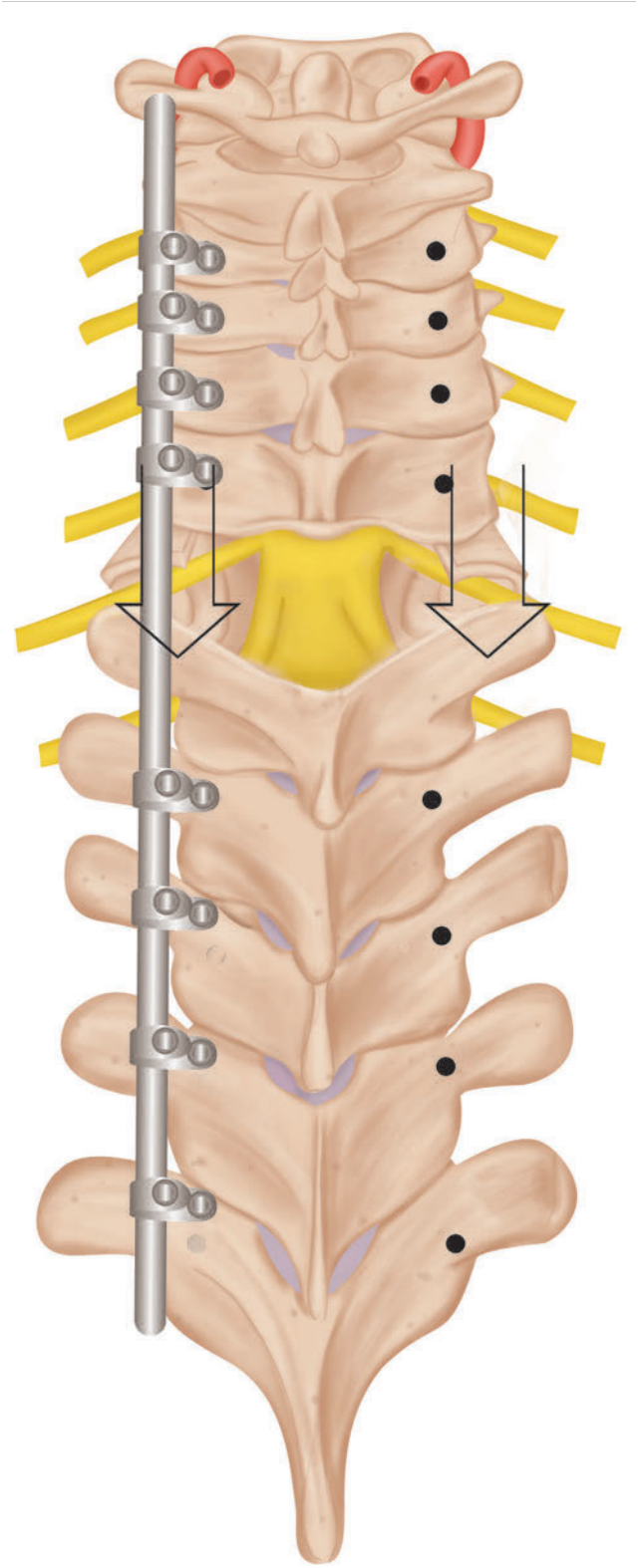

Fig. 69.4 Reduction of osteotomy with bending and sliding of malleable rod.

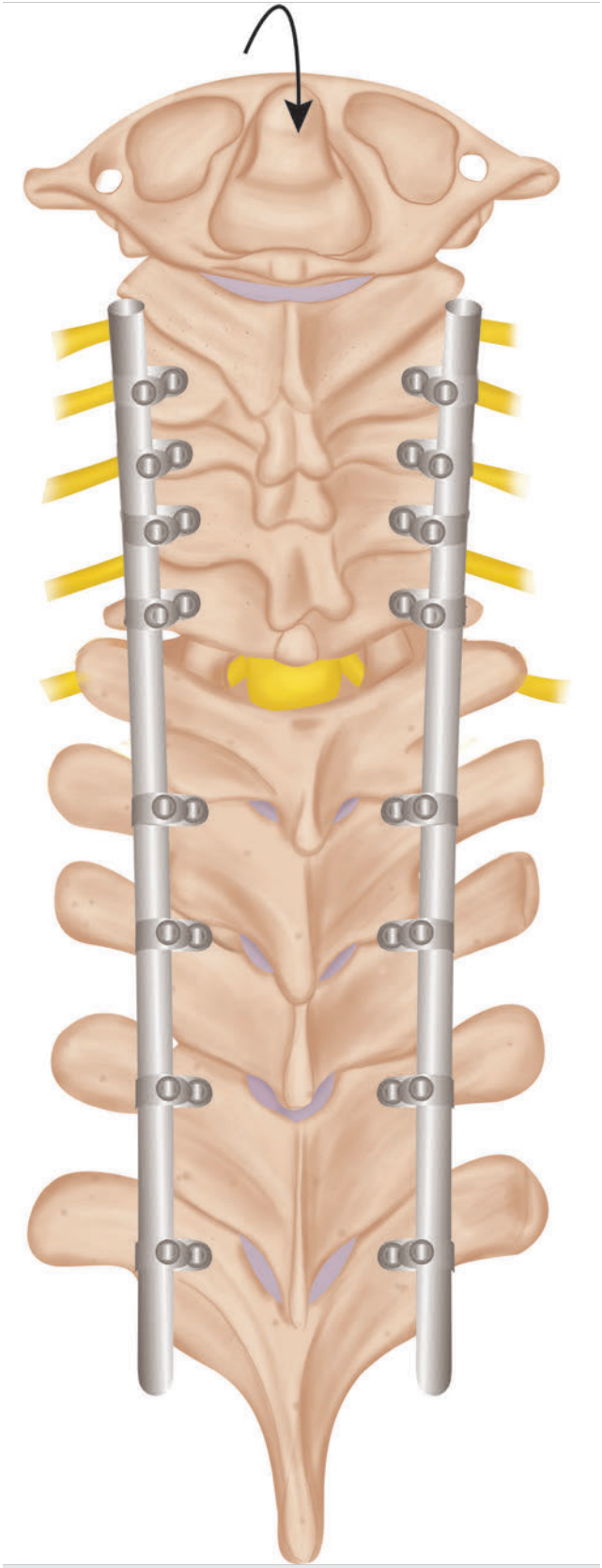

Fig. 69.5 Insertion of clamps and definitive rod on the right side.

69.7.5 Fixation and Fusion

If neural monitoring is satisfactory, the correction is then fixed with the instrumentation. If the malleable rod technique is used, the thoracic clamps are secured to the malleable rod, the other side is fixed with a contoured titanium rod, and finally the malleable rod is replaced (▶ Fig. 69.5). Decortication is performed, and osteotomy bone together with bone from the iliac crest is laid down. The wound is closed (▶ Fig. 69.6).

69.7.6 Postoperative Immobilization

Depending on the adequacy of fixation and bone stock, either an occipito-cervico-thoracic orthosis or a halo-thoracic brace is used for 3 months.

69.8 Bailout, Rescue, and Salvage Procedures

If monitoring indicates impaired spinal cord function, the correction should be reversed. If function does not return, the implants should be removed. If correction is lost postoperatively, a supplemental anterior approach may be required. If an inappropriate degree of correction severely compromises function, remedial corrective surgery may be required.

Pitfalls

- Difficulties may be encountered with intubation and patient positioning.
- The most significant potential problem is spinal cord or nerve root injury, due to translation during reduction, kinking, and compression of the cord or roots, or from instrumentation misplacement.
- Internal fixation may be inadequate, leading to loss of correction.
- Finally, undercorrection or (especially) overcorrection of the deformity may pose functional problems postoperatively.

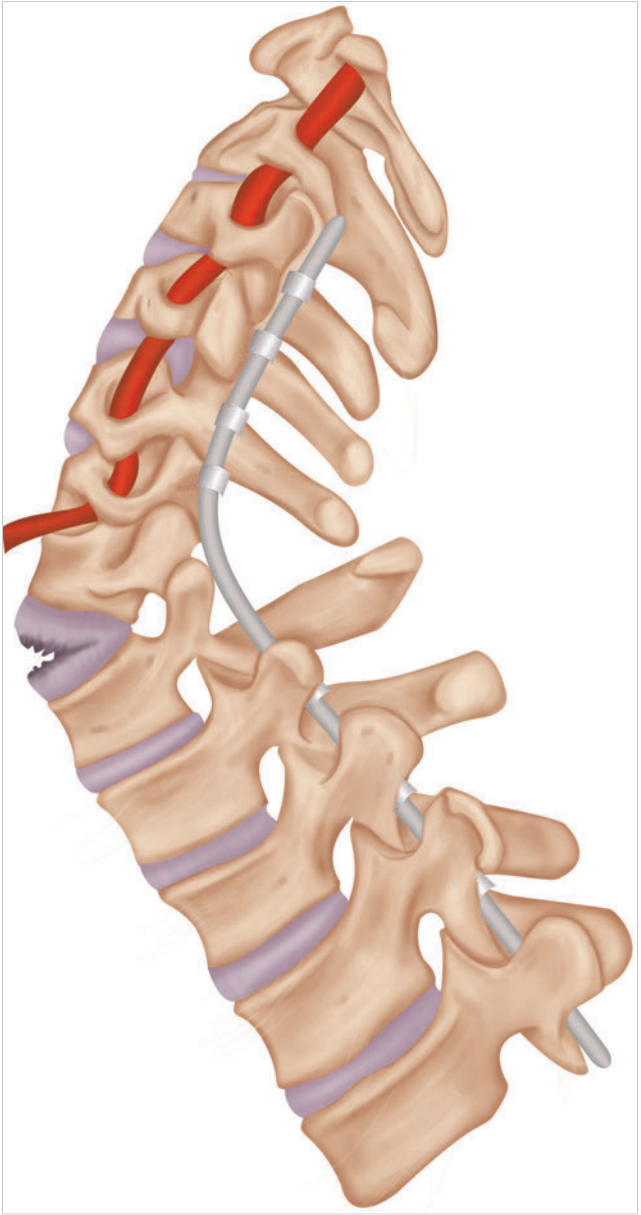

Fig. 69.6 Lateral appearance of completed osteotomy with definitive rods.

70 Posterior Smith–Peterson, Pedicle Subtraction, and Vertebral Column Resection Osteotomy Techniques

Vijay Shekarappa, Alpesh A. Patel, Gregory D. Schroeder, and Jason W. Savage

70.1 Description

Adult spinal deformity includes idiopathic curves as well as de novo or degenerative scoliosis, which may result in coronal and/or sagittal plane imbalance. Several recent studies have shown that positive sagittal plane deformity is directly associated with decreased health-related quality of life (HRQOL) outcome scores, and postoperative improvement in sagittal plane alignment has been shown to significantly improve patient outcomes.

Historically, the correction of a fixed sagittal plane deformity was accomplished through a circumferential approach with combined anterior and posterior reconstruction to re-establish spinal alignment. More recently, posterior-based spinal osteotomies have become the preferred techniques for correction of sagittal plane deformity. Posterior spinal osteotomies in combination with pedicle screw fixation are powerful methods to realign the spine in the coronal and/or sagittal planes through a posterior approach alone. It can provide a correction equivalent to a combined anterior and posterior approach, obviating the morbidity associated with anterior releases and corpectomies. Posterior spinal osteotomies include the Smith–Peterson osteotomy (SPO), pedicle substraction osteotomy (PSO), and vertebral column resection osteotomy (VCR). These are technically challenging procedures that require surgical expertise and a thorough knowledge of spinal anatomy, sagittal alignment, indications, surgical techniques, and potential complications.

70.2 Key Principles

Global sagittal alignment is assessed by a vertical line dropped from the center of the C7 vertebral body and is termed the C7 plumbline or sagittal vertebral axis (SVA) (▶ Fig. 70.1**a**). In a sagittally balanced spine the SVA passes through the posterior superior corner of the S1 vertebral body. If it falls anteriorly or posteriorly, the sagittal balance is said to be positive or negative, respectively. Regional sagittal alignment is assessed by T5–T12, T10–L2, and T12–S1 Cobb angles (▶ Fig. 70.1a). More recently, the role of the pelvis with regards to standing sagittal spinal alignment has been investigated. Three pelvic parameters have been described in the literature (▶ Fig. 70.1b). Pelvic incidence (PI) is a morphologic parameter, which has been demonstrated to define lumbar alignment, and specifically the degree of lordosis. In general, lumbar lordosis (LL) should match pelvic incidence (PI = LL ± 9 degrees). Pelvic tilt (PT) is a dynamic pelvic parameter that measures pelvic version, and often acts as a compensatory mechanism to help maintain an upright posture in the setting of sagittal malalignment (▶ Fig. 70.2). Hip extension and knee flexion are other compensatory mechanisms that result in the classic "crouched gait" often seen in these patients.

A sagittally balanced spine is essential for maintaining erect posture with minimal energy expenditure as described by Dubousset's cone of economy concept (▶ Fig. 70.3). Increasing positive sagittal imbalance causes the body to assume a position towards the periphery of the cone, which results in increased muscular effort and energy expenditure causing pain, fatigue, and disability. If the body is shifted beyond the periphery of the cone, external supports like a cane, crutch. or walker may be required to maintain balance. A positive sagittal balance and increased PT strongly correlates with poor HRQOL scores. Failure to restore a SVA of < 50 mm and PT of < 20 degrees in spinal fusion surgeries is associated with poor surgical outcomes. Posterior-based spinal osteotomies are the primary tool in restoring sagittal alignment and spinopelvic harmony.

70.3 Expectations

The choice of osteotomy is dependent on the goals of the procedure, the correction requirements, the underlying etiology of the deformity, the native bone quality of the patient, and anatomical variations that may be present. Each type of osteotomy has specific advantages as well as inherent limitations (▶ Fig. 70.4). They can be used individually or in combination to achieve the desired correction. The Smith–Peterson osteotomy offers up to 10 degrees of correction per level. This can be performed at any level in the thoracolumbar spine and is the ideal osteotomy in mild-to-moderate deformity with mobile disk spaces. This osteotomy requires lengthening of the anterior column, and therefore cannot be performed in the circumfirentially fused spine. Posterior column osteotomies are powerful correction tools when performed over multiple levels in the presence of mobile disk spaces. The pedicle subtraction osteotomy is a more powerful technique that can reliably achieve 30 degrees of correction at a single level. If the disk space above is included in the osteotomy, an additional 10 to 15 degrees of correction can be obtained. This is a closing three-column wedge osteotomy that hinges on the anterior column and causes shortening/closing of the middle and posterior columns. A vertebral column resection is the removal of an entire segment (vertebral body and disk above/below) and provides profound correction, often up to 40 to 60 degrees from a single level. This is the most complex osteotomy to perform, and is associated with significant morbidity and a high risk of complications.

70.4 Indications

The primary indication for posterior spinal osteotomies is symptomatic fixed or partially correctable sagittal deformity, which can be either global or regional in nature. The conditions causing global sagittal deformities are characteristically trimodal in age distribution. Sheurmann's kyphosis is seen in adolescents; kyphosis in the middle aged is commonly due to inflammatory disorders like ankylosing spondylitis; in the elderly, it is due to degenerative disorders. Trauma, infections, tumors, and iatrogenic causes result in angular deformities and can occur at any age.

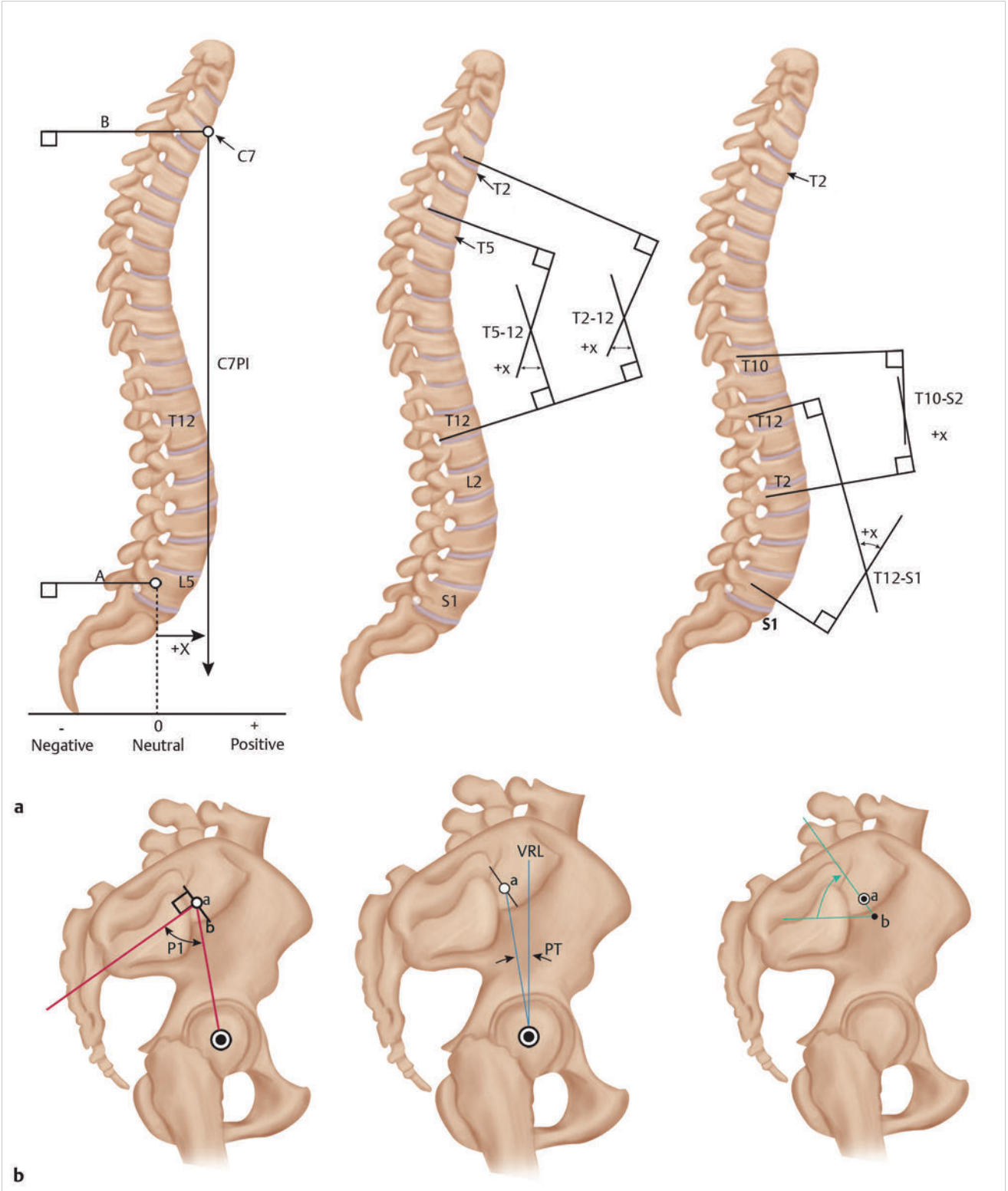

Fig. 70.1 **(a)** Sagittal vertebral axis and regional sagittal alignment. T5–T12 angle represents thoracic kyphosis and normally ranges from 20–50 degrees, the T10–L2 angle represents thoracolumbar region, which is typically neutral, and the T12 –S1 angle represents lumbar lordosis (LL), which ranges from 31 to 79 degrees. (**b**) Pelvic parameters: Pelvic incidence (PI) is the angle between the line perpendicular to the sacral end plate and a line joining the midpoint of sacral plate and center of the femoral heads (Mean = 52 degrees, range 34–84 degrees). Pelvic tilt (PT) is the angle between the line joining the center of sacral end plate and head of femur with the vertical (Mean = 12 degrees, range 5–30 degrees). Sacral slope (SS) is the angle between the sacral end plate and the horizontal (Mean = 40 degrees, range 20–65 degrees). PI = PT + SS, PI = LL ± 9.

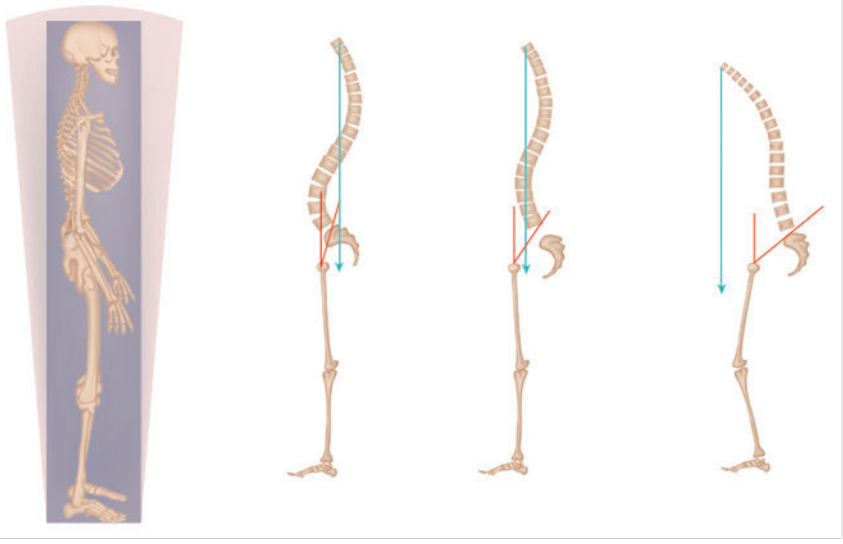

Fig. 70.2 Progressive increase in sagittal vertebral axis with compensatory mechanisms.

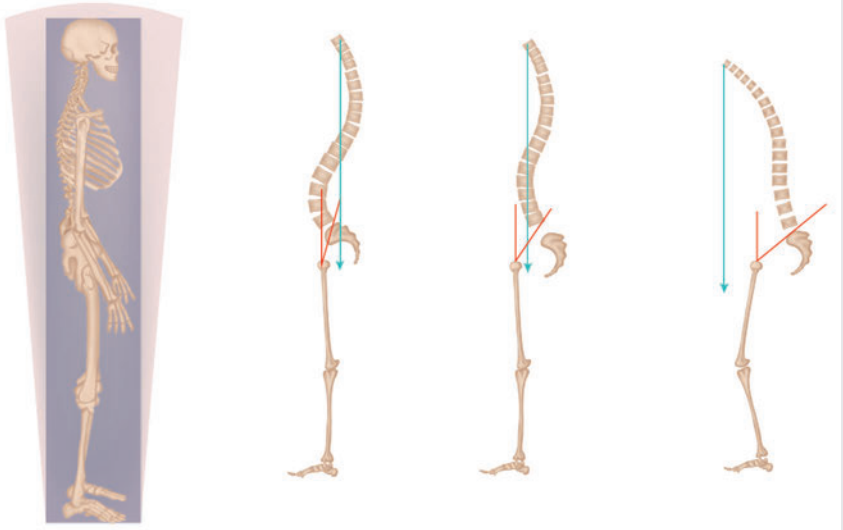

Fig. 70.3 Dubousset's cone of economy concept illustrates the importance of spinopelvic balance in maintaining an upright posture and minimizing energy expenditure with standing and walking. Increasing positive sagittal imbalance causes the body to assume a position towards the periphery of the cone, which results in increased muscular effort and energy expenditure causing pain, fatigue and disability. If the body is shifted beyond the periphery of the cone, external supports such as a cane, crutch, or walker may be required to maintain balance.

The Smith–Peterson osteotomy is ideal in mild-to-moderate sagittal plane deformity with a mobile anterior column. The pedicle subtraction osteotomy is commonly performed for fixed sagittal plane malalignment, often in the presence of previous fusion surgery. A PSO is most commonly performed in the lumbar spine. Recent studies have shown that the level of PSO (L3 vs. L4) does not affect the degree of correction; however, lower lumbar PSOs correlate with an increased correction in PT, but not LL. An asymetric PSO can be used to correct both sagittal and coronal plane deformity. Finally, vertebral column resection is the osteotomy of choice for sharp, angular kyphotic deformities in the thoracic spine.

70.5 Contraindications

Surgical correction of adult spinal deformity is fraught with complications. Patients must be optimized medically prior to entertaining the idea of performing reconstructive surgery to improve spinal alignment. Severe osteoporosis is a relative contraindication due to the biomechanical disadvantage that leads to a high incidence of mechanical failure of the instrumentation used to maintain the correction.

70.6 Special Considerations

The flexibility of the sagittal plane deformity should be evaluated. This can be done with the use of supine X-rays with or without a bolster to assess for a change in the degree of LL due to positioning alone. Magnetic resonance imaging (MRI) or computed tomography (CT) can also be used to evaluate the status of the disk spaces and facet joints. Advanced degenerative changes on MRI or CT with evidence of ankylosis (facet fusion, bridging anterior osteophyte formation, circumferential fusion, etc.) is associated with a more rigid deformity, whereas mobile disk spaces anteriorly often allows for some flexibility with positioning and allows for anterior column lengthening with posterior column-based osteotomies. Surgical correction and technique are critically dependent on differentiating rigid and flexible deformities.

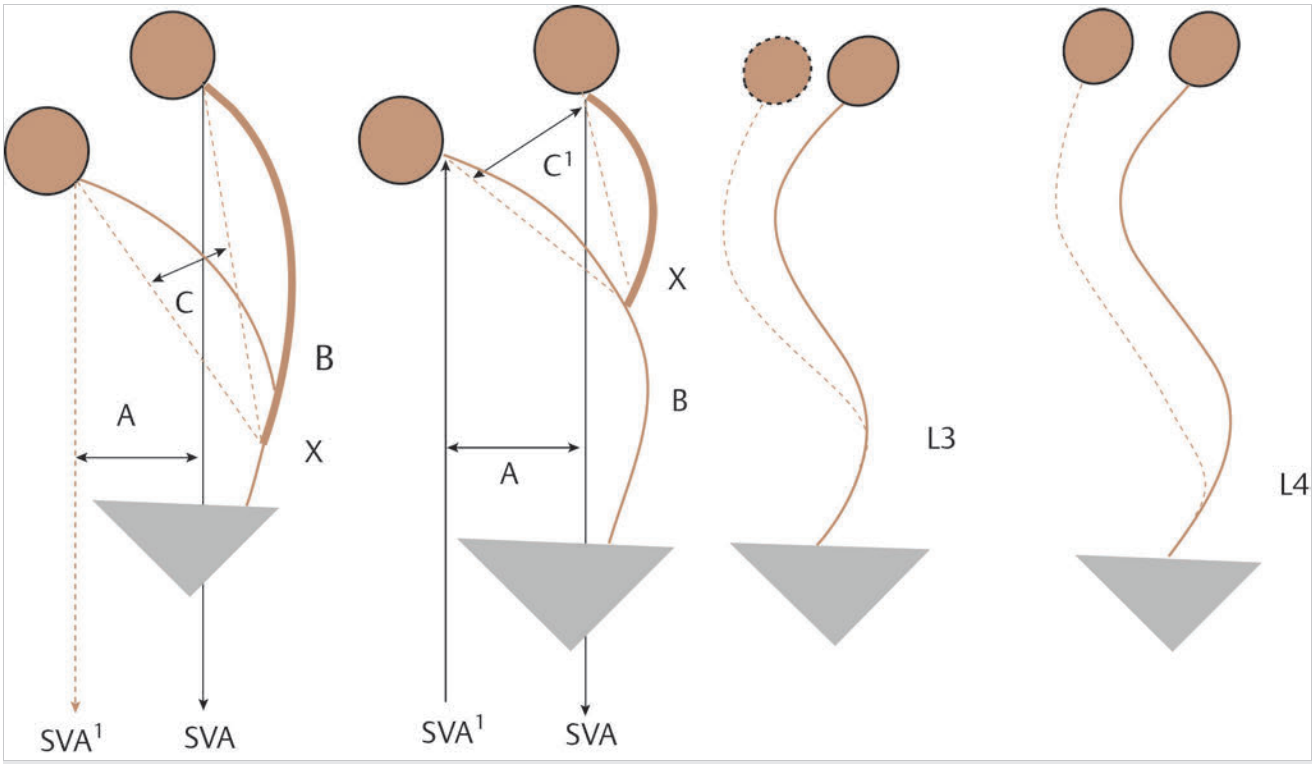

Fig. 70.4 **(a)** Smith–Peterson osteotomy, **(b)** pedicle subtraction osteotomy, and (c) vertebral resection osteotomy. SVA, sagittal vertebral axis.

70.6.1 Preoperative Planning

A meticulous preoperative plan is essential to achieve predictable restoration of sagittal alignment, and therefore good clinical and radiographic outcomes. All patients should be initially evaluated with standing scoliosis (36 inch) X-rays with the knees and hips extended. The clavicle position is the optimal patient stance for obtaining accurate and reproducible lateral scoliosis X-rays. This is done with the elbows fully flexed and the wrists/hands placed in the supraclavicular fossa with no external supports.

The regional and global alignment must be measured, with specific attention paid toward SVA, thoracic kyphosis, and LL. Spinopelvic parameters should also be documented, and the degree compensation through PT noted. In the setting of previous spine surgery, a CT scan should be obtained to accurately evaluate for pseudarthrosis and appropriate positioning of the instrumentation. A supine lateral scoliosis X-ray with or without a "bump" can be taken to assess the flexibility of the sagittal plane deformity. The realignment objectives to achieve spinopelvic harmony are a SVA < 5 cm, PT < 20 degrees, and LL = PI ± 9 degrees. Preoperative hip flexion contractures should be corrected prior to spinal reconstruction, as this often significantly contributes to the overal malalignment.

70.6.2 Calculating the Angle of Osteotomy

A number of methods have been described for calculating the angle of osteotomy required for correcting spinal deformity and malalignment. However, many of these methods are complex and difficult to implement in practice.

A predictive model for key spinopelvic parameters utilizing a morphologic pelvic parameter (PI) and modifiable spinal parameters through surgery (LL and thoracic kyphosis), allows prediction of postoperative sagittal alignment. It is now commonly accepted that the degree of lordosis required by a given subject may be estimated with the formula: LL = PI + 10 degrees. Several computer-based programs are now available that use this predictive formula to aid in preoperative realignment planning. Based on the nature of the deformity (rigid vs. flexible) and degree of sagittal plane deformity, a generalized algorithmic approach can be used to help guide operative reconstruction (▶ Fig. 70.5).

70.7 Special Instructions, Positioning, and Anesthesia

The patient is positioned prone on a radiolucent frame with four to six posts allowing the abdomen to be free of pressure. The patient is typically "built up" on a chest pad with the hips in maximum extension to render the lumbar spine as lordotic as possible. This can be achieved on a standard open Jackson table or a specialized osteotomy frame. In cases where there is a mobile anterior column, patients often obtain a reasonable degree of correction simply by proper positioning. The ability to "reflex" the table electronically will aid in the closing of the osteotomy.

A Mayfield head holder is often used to prevent any pressure on the eyes througout the duration of the procedure.

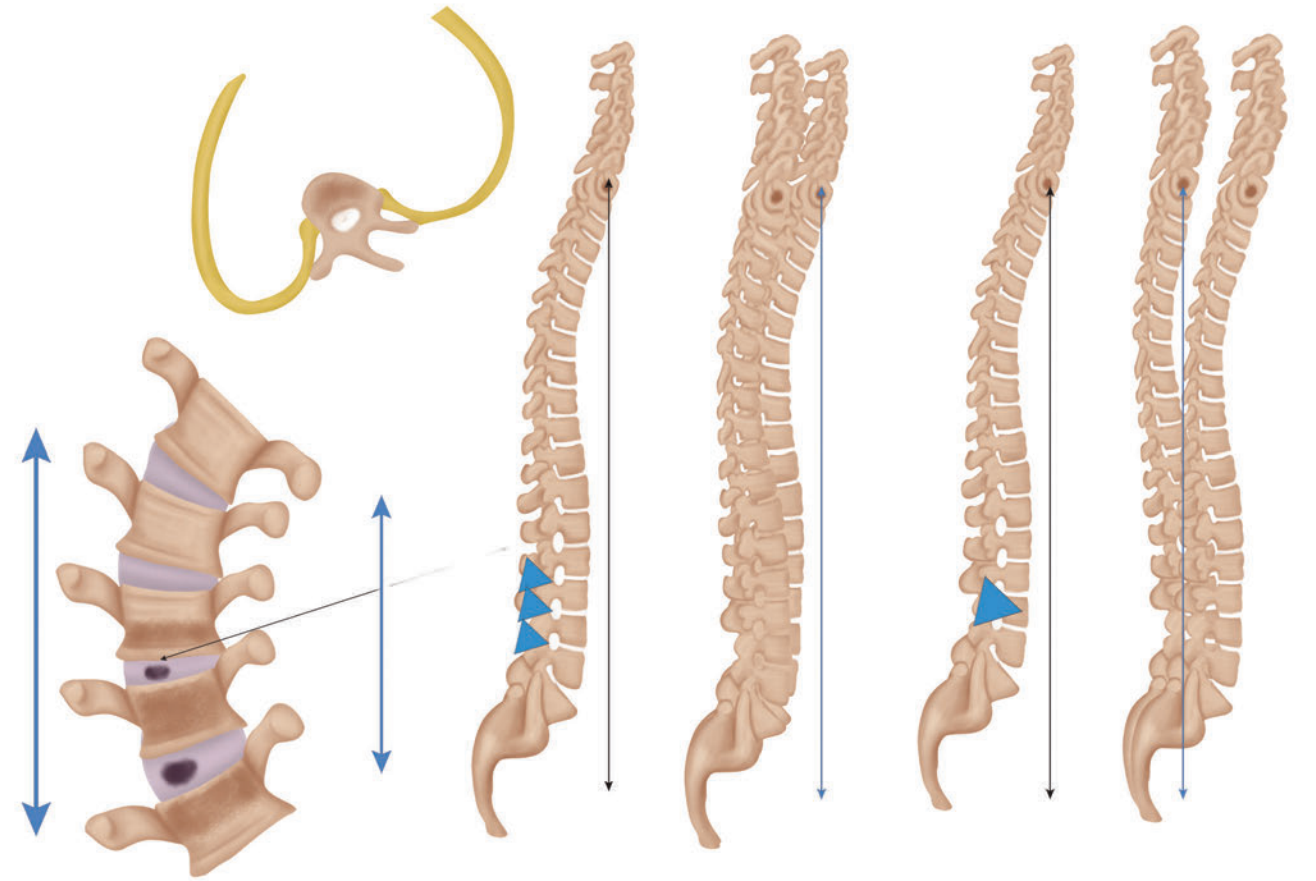

Fig. 70.5 Algorithm for selecting the type of osteotomy.

Intraoperative monitoring is used (somatosensory evoked potentials [SSEPs], transcranial motor evoked potentials [tcMEPs], electromyograms [EMGs]) to help recognize and prevent neurologic injury, especially at the time of osteotomy closure.

70.8 Tips, Pearls, and Lessons Learned

Patients should have a thorough preoperative evaluation, and medical comorbidities should be optimized prior to surgery. The care of these patients should be multidisciplinary, with involvement of the spine surgeon, neuroanesthesiologist, critical care specialist, and internal medicine physician.

The exposure, removal/revision of instrumentation, placement of pedicle screws, and meticulous takedown of a pseudarthrosis should be done prior to starting the osteotomy. Placing the pedicle screws first allows for identification of normal anatomical landmarks, as well as prevents the instrumentation from getting in the way during the complex part of the osteotomy. Hemostatic agents, such as a Gelfoam (Pfizer Pharmaceuticals) and FloSeal (Baxter Healthcare) should be used to help maintain hemostasis throughout the operation. Always check with anesthesia before starting the osteotomy. If there has been a significant amount of blood loss and/or the patient is not hemodynamically stable, the osteotomy should be staged and done on another day.

In general, either cobalt chrome or stainless steel rods should be used to help prevent loss of correction and rod failure. A tap should *not* be used in osteoporotic bone in an effort to maximize pedicle screw purchase.

70.9 Difficulties Encountered

Complex adult reconstructive procedures with or without spinal osteotomies are fraught with complications. Proper patient selection, perioperative optimization, and preoperative planning are crucial to minimize intraoperative and postoperative adverse events. Instrumentation failure, loss of reduction, and/or proximal junctional failure are relatively common complications associated with osteotomy procedures. Decreased bone mineral density (osteopenia or osteoporosis) may increase the risk of developing a mechanical failure; therefore, a preoperative dual-energy X-ray absorptiometry (DXA) scan should be obtained, and bone health optimized prior to surgical intervention. This is often accomplished with calcium and vitamin D supplementation, and the use of a bisphosphonate or anabolic agent (teraparatide).

Postoperative radiculopathy may occur if an inadequate decompression is performed prior to the osteotomy closure. A thorough central, lateral recess, and foraminal decompression

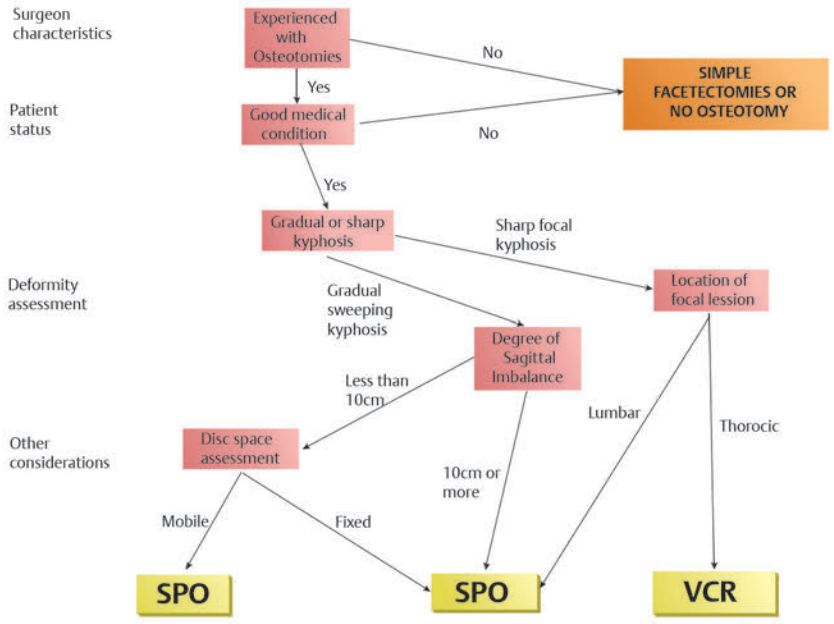

Fig. 70.6 Smith–Peterson osteotomy (SPO) is a complete facetectomy with a chevron-type resection of the inferior and superior facet complex. Closure of the osteotomy results in lengthening of the anterior column through a mobile disk space. VCR, vertebral column resection osteotomy.

must be completed to prevent postoperative neurologic symptoms. If there are changes in the intraoperative neuromonitoring (SSEPs, MEPs) signals after osteotomy closure, the surgeon must evaluate the decompression and identify any areas of residual stenosis or buckling of the dura. In a Smith–Peterson osteotomy, the superior articular facet should be removed down to the cephalad aspect of the corresponding pedicle, whereas for a PSO, a foraminal decompression from the pedicle above to the pedicle below the level of the osteotomy must be performed to prevent nerve root compression after osteotomy closure.

70.10 Key Procedural Steps

70.10.1 Smith–Peterson Osteotomy

The Smith–Peterson osteotomy is a complete facetectomy, with a chevron-type resection of the inferior and superior facet complex (▶ Fig. 70.6). An osteotome or high-speed bur is used to remove the inferior facet of the cephalad vertebra. The posterior ligaments (supraspinous and interspinous) and ligamentum flavum are resected to expose the dura. Gelfoam or FloSeal is used to control epidural bleeding. The superior articular facet is then removed with either a bur or Kerrison rongeurs. Once the osteotomies are completed, the pedicle screws or other implants are placed, and closure is achieved by compression, postural effects, table manipulation, or a combination of maneuvers. Closing the osteotomy causes narrowing of the neural foramen; therefore, a compete superior facetectomy and undercutting of the lamina is essential to prevent nerve root impingement.

At times, to maximize the correction at a level and improve fusion rates, an interbody device is placed in the anterior one-third of the disk space. This increases the height of the disk and provides an anterior pivot point and moves the axis of rotation forward, which increases the angle of closure. It also has the advantage of providing graft material in the anterior column to increase fusion success. It is important not to place an implant that covers a large portion of the end plate, as this has the potential to block the closure of the posterior disk space, which will limit the amount of correction obtained through the osteotomy. This type of osteotomy can be done at mutliple levels. However, lenghtening of the anterior column may result in serious vascular and gastrointestinal complications; hence, correction of more than 60 degrees is not recommended.

70.10.2 Pedicle Substraction Osteotomy

After placing pedicle screws above and below the osteotomy level, the precision-cut pedicle subtraction osteotomy begins with placement of a pedicle preparatory hole. With no implant in place, a prepped and tapped pedicle is very useful to maintain orientation while the bony resection is taking place. The bony removal of the posterior elements then begins. The removal should be centered at the pedicle that is to be removed. The amount of bone to be removed should be calculated to match the amount of closure needed. It should involve the superior and inferior facet of the osteotomy level and the inferior facet of the cephalad level and the superior facet of the level below. The decompression should be bilateral from the pedicle above to the pedicle below, resulting in two nerve roots exiting a single neural foramen. In the case of a prior posterior fusion mass, a fusion mass removal is performed. This is done with osteotomes, rongeurs, and curettes to save all bone for later fusion. The osteotomy can be fine-tuned with a high-speed drill. It is helpful to undercut the posterior bone edge in a "keystone" fashion. This decreases any dural impingement.

The pedicle is then fully removed with a rongeur and a drill. Care should be used to fully remove the pedicle base. Small spicules of bone can result in radiculopathy once the osteotomy is closed. In revision cases, it is also important to remove all scar tissue from the dura to avoid soft tissue crowding once closure

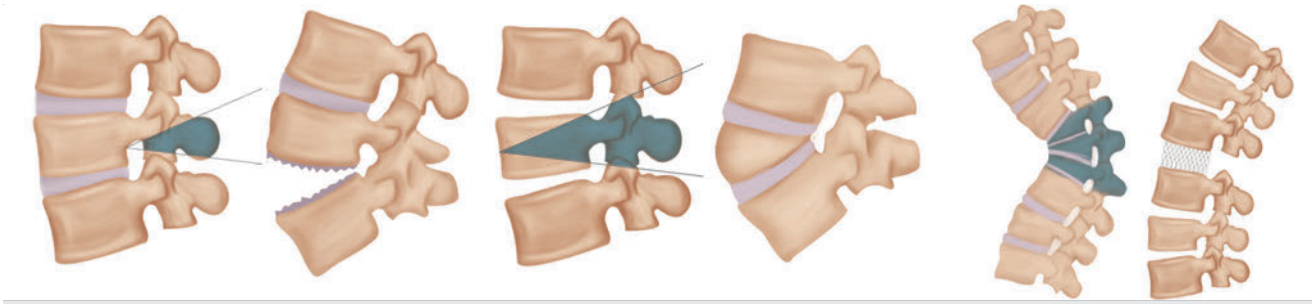

Fig. 70.7 Pedicle subtraction osteotomy: The pedicles are removed in their entirety, and a wedge-shaped osteotomy is created in the vertebral body, with the pivot point being the anterior vertebral body wall. Closure of the osteotomy results shortening of the middle and posterior column.

has been done. Once the pedicle has been removed, dissection of the vertebral wall is done bilaterally. Penfield dissectors and elevators are used, with the dissection being performed from the level of the disk that immediately lies above the resected pedicle caudally as much as the resection needs to go. The body should be dissected laterally along the vertebral body as far as necessary to get adequate exposure and resection.

The segmental artery can be swept caudally in a subperiosteal fashion. This can typically be done without difficulty over two-thirds of the vertebral body. If the vessel begins to bleed, bipolar cautery at a higher setting can be used. If this does not work, pack the area. Bleeding typically resolves with osteotomy closure. We have not had to stop and move to a flank incision for control of the aorta, but this would be a reasonable maneuver should bleeding persist.

Bone is removed with rongeurs and a drill, in a precise wedge based on the calculated degrees of closure. The apex of the wedge is at the anterior vertebral body wall. This wall should be preserved as a pivot point. The base of the osteotomy is at the floor of the spinal canal (▶ Fig. 70.7). This is more easily done today with specialized vertebral body retractors to assist in exposure. The cancellous bone is then removed with curettes and rongeurs in a wedge-shaped fashion matching the cuts on the lateral walls. Again, all bone is saved for later grafting. Drills can be used for final shaping. The final bone resection is the posterior vertebral body wall, or the floor of the spinal canal. The lateral edge can be removed with rongeurs. The final removal of the vertebral posterior body is done with an impaction technique using a reverse curette into the vertebral body cavity created by the resection. This can be done with curettes or with specialized impactors, which again makes the procedure a bit smoother.

It is important to place a temporary holding rod to maintain vertebral body orientation and prevent early collapse of the body when the posterior wall is removed. This is occasionally necessary earlier in the procedure. With all bone resected and the canal and root exit zones inspected for any tissue that could impinge on neurologic structures, the osteotomy is closed. Typically, very little compressive pressure is needed on the screws above and below the osteotomy. The osteotomy is closed by gentle pressure by hand on the spine on each side of the osteotomy. If a standard operating table is used, the patient's body can also be flexed. The closure is further completed by hyperlordosing the rod in the area of the osteotomy and adding a cantilever force. Final closure is performed by gentle rod compression. If more force is needed and there are posterior elements, a compression hook combination can be put in the bone above and below the osteotomy. A third rod can be used to get added compression. Once the final rod is in place, the third rod and its hooks are generally removed. Anteroposterior and lateral 14- × 36-inch scoliosis radiographs are used to confirm osteotomy closure and ensure there is no translation. The posterior elements should be completely or nearly completely closed and not translated. The lateral wall closure and the root exit zones are inspected. The roots above and below the pedicle are now both contained in a superforamen.

The advantage of precision-cut technique is the precise closure of the bone, giving the exact calculated resection. Ideal bone contact leads to improved rates of fusion and less stress on the construct before fusion. All bone cuts should be symmetric unless coronal correction is then needed. If this is the case, the side to which coronal deviation is needed is cut larger than the other side by the amount needed to obtain coronal correction.

70.10.3 Vertebral Column Resection

This technique is an extension of the pedicle subtraction precision-cut technique. It can be performed effectively from T3–L1 (inclusive). All implants are placed via a midline incision, with the exception of the osteotomy levels. Again, the osteotomy-level pedicles are prepped. The erector spinae muscle is then dissected on its lateral border and mobilized. Access and dissection of the ribs that articulate with the disks above and below the osteotomy level is then performed. Up to 10 cm of the ribs are removed unilaterally and saved for graft. Somewhere between 2 and 3 cm of the ribs can be removed from the opposite side to enhance closure of the osteotomy and help with vertebral resection. A lateral extracavitary dissection is then performed to the anterior vertebral body. It is often necessary to coagulate one and at times both segmentals at the level of resection. With the rib heads removed, attention is turned to the vertebral resection.

The vertebral resection begins with a posterior removal of the lamina (or fusion mass) and the pedicles. The vertebral body is then fully resected to include the disks above and below the body. The end plates of the bodies above and below the resection are feathered with curettes and drills. The posterior vertebral body wall is then carefully removed with impactor (▶ Fig. 70.8).

In vertebral column resection, an anterior cage is placed as a pivot point and gradual posterior closure is performed while pivoting on the cage. In an X osteotomy, the anterior

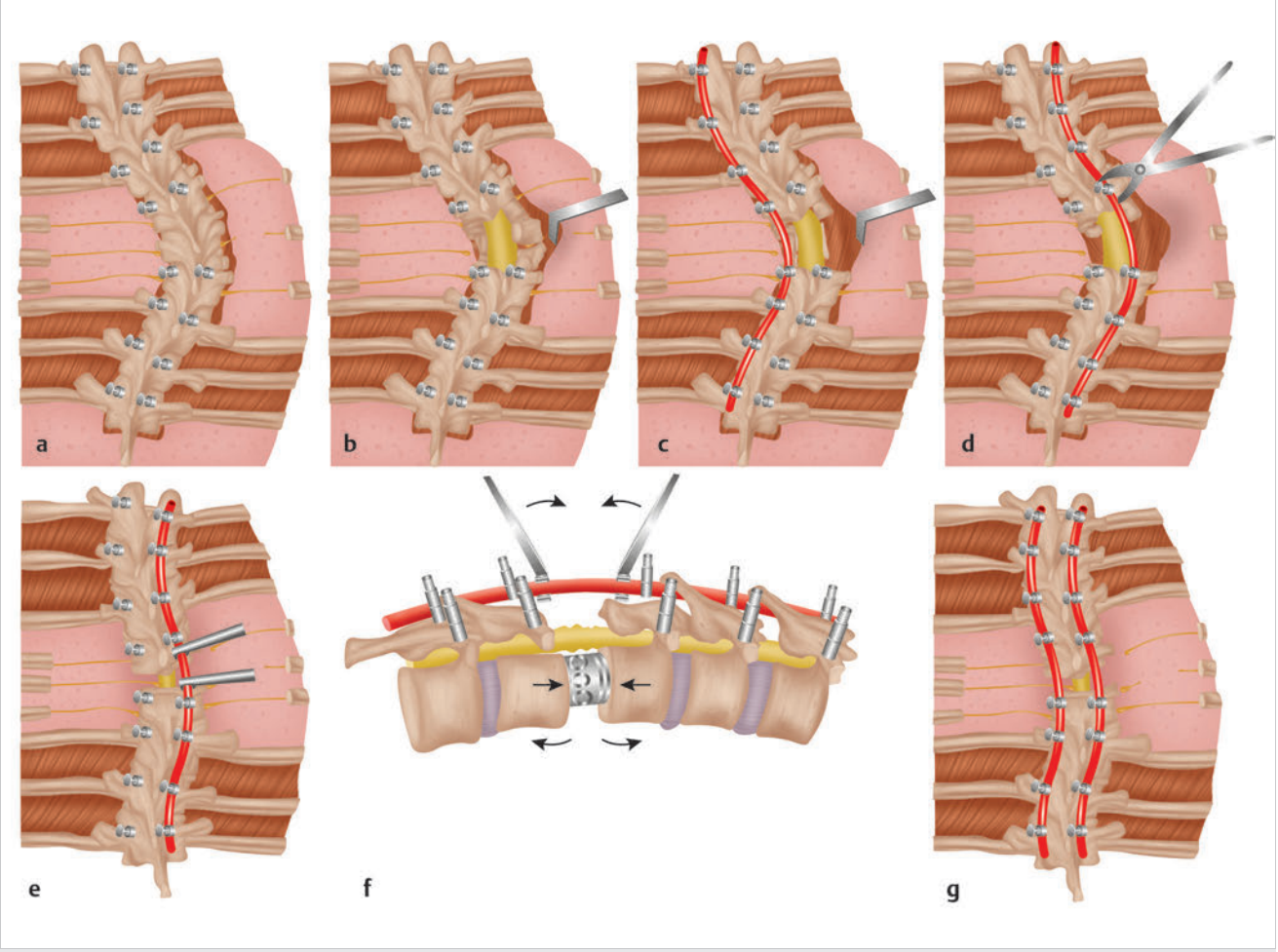

Fig. 70.8 (**a–g**) Steps of a vertebral resection osteotomy.

longitudinal ligament is cut. The pivot point is either the preserved posterior vertebral body wall or a posterior vertebral body pivot cage that is placed after resection. If the posterior vertebral body wall is used as a pivot, care must be taken that it pivots and does not buckle back into the canal. For this reason, many prefer a structural implanted pivot cage.

This X osteotomy technique is an anterior opening and posterior closing osteotomy done from a posterior approach. The axis of rotation moves to the pivot that is near to or at the spinal canal. As a result, this has the advantage of minimal canal length change, either in compression or extension. This allows the largest amount of closure of any osteotomy. It has the disadvantage of instability through translation during closure.

70.11 Bailout, Rescue, and Salvage Procedures

Occasionally, a patient in whom multiple Smith–Petersen osteotomies were planned, the osteotomies will not close down, implying that there is an ankylosed disk space anteriorly. If the desired correction cannot be achieved as planned, two adjacent Smith–Petersen osteotomies can be converted into a single pedicle subtraction osteotomy. Such a maneuver reliably allows one to salvage a situation in which a Smith–Petersen osteotomy plan does not close and yield the correction previously anticipated.

Pitfalls

- The ideal ammount of correction varries by idivduals, and the goal adult deformity opoeration should be to maintain “Spino-pelvic harmony” which results from an SVA < 5 cm, PT < 20 degrees, and LL=PI + /- 9 degrees. Failure to understand the relaitionship between the spine and the pelvis will result in poor outcomes.
- Obtaining intraoparetive full length films is critical in defromity surgery. Failure to obtain these images may result in more or less correction than planned.
- When perfomring advanced posterior osteotomies it is cirtical to know where the nerve roots are at all times. Failure to protect the nerve roots can lead to significant neural deficits.
- Complex posterior osteotomies should only be performed in an institution with a multi-disciplinary care team availiable, including the spine surgeon, neuro-anesthesiologists, critical care specialists, and interal medicine physicians. Both medical and surgical complications are common in these cases, and it is critical that the resources are available to deal with the complications.

71 Intraoperative Computed Tomography–Guided Instrumentation for Deformity Spine Surgery

Sadashiv Karanth and Daniel R. Fassett

71.1 Description

Placement of anchoring instrumentation, such as pedicle screws, can be very challenging in patients with spinal deformities. The rotational abnormalities in scoliosis dramatically change the angulation of pedicle screw insertion in comparison to the normal spine; often, the pedicles in these patients are smaller than normal. In addition, in degenerative deformities, there is often bony overgrowth that can obstruct the visualization of normal anatomical landmarks making screw insertion much more challenging. In some situations, patients have deformities adjacent to previous uninstrumented fusions or fusions with hooks and rods. Placement of pedicle screws through these prior fusion masses is troublesome as the normal anatomy cannot be visualized and the tactile feel of pedicle cannulation is altered.

Use of intraoperative computed tomography- (CT-) guided navigation may be useful for placement of anchoring instrumentation for cervical, thoracic, and lumbar deformity correction. Navigation technologies have potential benefits in deformity surgery: (1) reduce screw misplacement, (2) improve screw pullout strength by targeting cortical bone in the vertebral bodies, (3) reduce operative time, and (4) reduce blood loss.

71.2 Key Principles

Placement of anchoring instrumentation using CT-guided navigation.

71.3 Expectations

Accurate placement of hardware with better cortical purchase especially in challenging deformities, shorter operation and anesthesia time, less blood loss leading to less need for transfusion, postoperative ventilation, and quicker recovery from surgery.

71.4 Indications

- Multiplanar deformed spine
- Narrow pedicles
- Poor anatomical landmarks for instrumentation
- Simple instrumentation in obese patients

71.5 Contraindications

None.

71.6 Special Considerations

A large operating room is essential as plenty of floor space is needed to move and place the mobile CT around the patient. The operating room is already crowded with anesthesia equipment, scrub table(s), and the navigation system (computer and infrared position sensors).

71.7 Special Instructions, Positioning, and Anesthesia

Radiation protection is a must during the CT runs. Only the radiology technician remains in the operating room during the acquisition of the axial CT images. The radiology technician should wear lead protection and stand in a location relative to the machine to limit radiation exposure. Anesthesia and operating room staff should leave the operating room during the CT acquisition to prevent radiation exposure. Ventilation is held while the CT images are acquired, which takes approximately 15 seconds.

71.7.1 Positioning

- Use of a large operating room to accommodate the mobile CT
- Jackson table—for ease in allowing passage of the intraoperative mobile CT
- For cervical and upper thoracic instrumentation, position the upper limbs tucked and wrapped in line with the torso as abducted arms will prevent movement of the CT machine (▶ Fig. 71.1).
- Radiolucent Mayfield (▶ Fig. 71.2a, c) for cervical instrumentation to avoid artifacts. If this is done, one will need special adaptors to fix the head to the Jackson table (▶ Fig. 71.2b).

71.7.2 Intraoperative Preparation

- Place reference frame a sufficient distance away from the working area to prevent bumping of the frame (▶ Fig. 71.3).

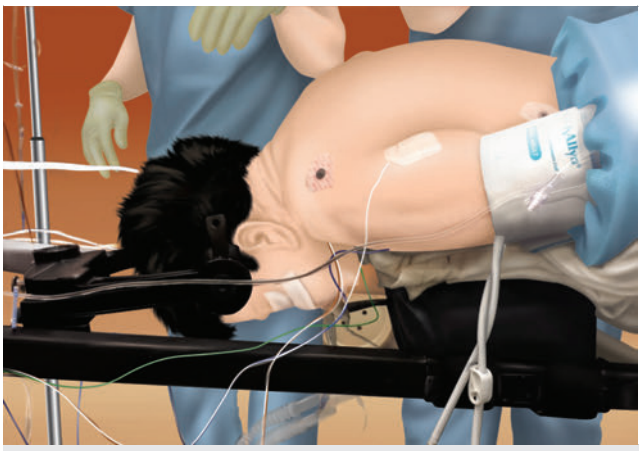

Fig. 71.1 Patient position: Head fixed on Mayfield and arm wrapped along torso.

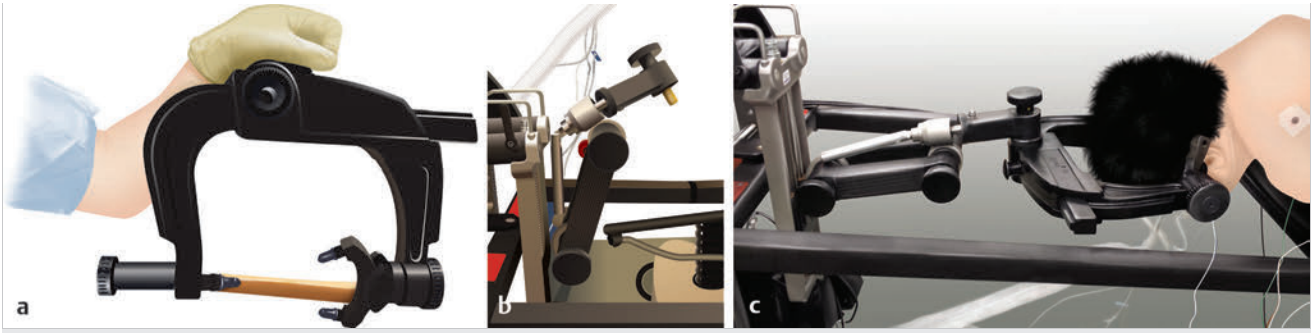

Fig. 71.2 **(a)** Radiolucent Mayfield, **(b)** adaptor, and **(c)** head held in position using both of them.

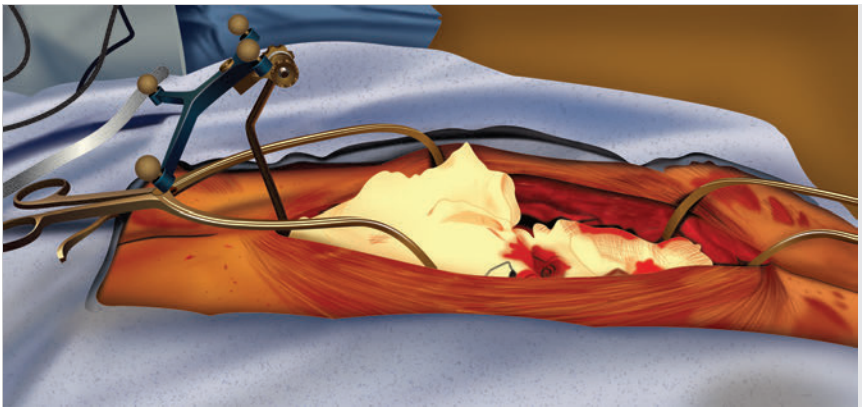

Fig. 71.3 Reference frame placed away from working area.

Fig. 71.4 Use of long drapes on either side prior to computed tomography scan.

- Arrange the camera in a location to reduce camera obstruction (may be at head of bed, at the patient's feet, or other location).
- We do not use separate CT draping. Instead, we use two fresh large half sheets for every CT run to cover the operative field (▶ Fig. 71.4).

71.8 Tips, Pearls, and Lessons Learned

71.8.1 Reference Frame

- Make sure that soft tissue retractors are well placed prior to obtaining the reference CT. Do not remove or adjust the retractors; this may inadvertently move the reference frame.

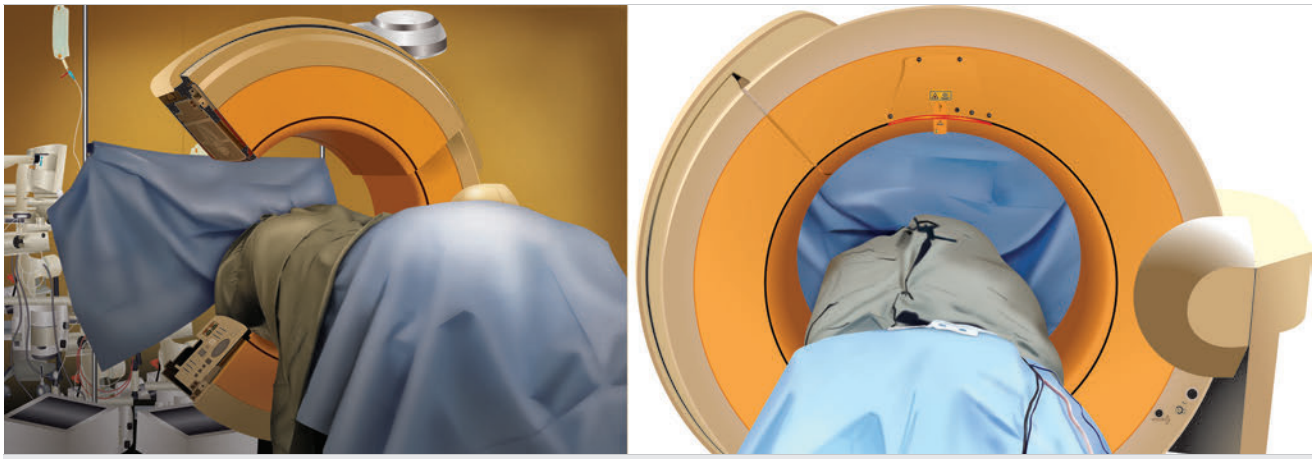

Fig. 71.5 (a, b) Placement of intraoperative computed tomography scanner.

- For revision instrumentation or extension of instrumentation, the original instrumentation can be used as an anchor for the reference frame.
- When occipital-cervical fusion is needed for cervical deformity correction, apply the occipital plate first on which the reference frame can be placed.

71.8.2 Timing for CT Imaging

Obtain a reference CT prior to decompression and creation of osteotomies. Place the instrumentation with navigation initially as this minimizes blood loss in comparison to performing a decompressive laminectomy prior to instrumentation.

71.8.3 Pedicle Screw Placement

- Use a power drill through a drill guide tube to drill the course of the pedicle screw. There is less force exerted on the spine with drilling of the pedicle screw trajectory in comparison to cannulation of a pedicle with a pedicle finder (gear shift). We believe that use of gear shift (pedicle finder) with greater force on the spine increases the risks of spine migration and loss of registration/accuracy.
- Use trajectory views on the navigation software to guide the drilling angles.
- Use tactile feedback during drilling with gradual tapping of the drill as it advances in the pedicle. If it does not feel like it is drilling in bone, stop advancing the drill and probe the course of the trajectory to confirm that the drill is still in bone.
- Consider that there could be a loss of accuracy in the navigation at any time. If something does not appear correct based on anatomy and surgeon experience, consider performing a new CT and reregistering the navigation.

71.9 Difficulties Encountered

Maneuvering the CT scanner with navigation system can be difficult in a small operating room. Careful attention needs to be made to avoid contacting the reference frame. It is very easy to bump this reference frame with instruments and cords during the procedure.

71.10 Key Procedural Steps

- Upon exposure of the spine the reference frame is firmly clamped to an osseous or immovable structure (e.g., spinous process, prior instrumentation) (▶ Fig. 71.3).
- Long drapes are used to keep the field sterile (▶ Fig. 71.4). The CT scanner is placed around the patient (▶ Fig. 71.5a, b). A scout X-ray is obtained once the CT is placed around the patient. This will guide the spinal levels that need to be scanned.
- Use the navigation guide to ascertain the trajectory for pedicle drilling (▶ Fig. 71.6). We aim for maximal length of cortical purchase for pedicle screws.
- A power drill is utilized through a guide tube that has a navigation array (▶ Fig. 71.7a). This allows the navigation software to visualize the drill in relation to the patient's anatomy, allowing the surgeon to drill the entire course of the screw trajectory. Drill the bone with a tapping motion to obtain tactile feedback while watching the advancement on the navigation screen (▶ Fig. 71.7b).
- Once the bone is drilled, tapping is done followed by placement of the screw.
- If there is any concern about appropriate positioning of the instrumentation, one can obtain an intraoperative CT of this area to confirm appropriate placement of hardware.

71.11 Bailout, Rescue, and Salvage Procedures

If there is any suspicion of inaccuracy in guidance, the CT scan needs to be repeated.

Pitfalls

CT or navigation systems stop functioning:
- Restart the systems.

Unable to navigate:
- Make sure the navigation system is connected to the infrared camera as well as CT scanner. The infrared camera sees the reference frame as well as the navigating tool.
- Clean and dry spheres of the reference frame.

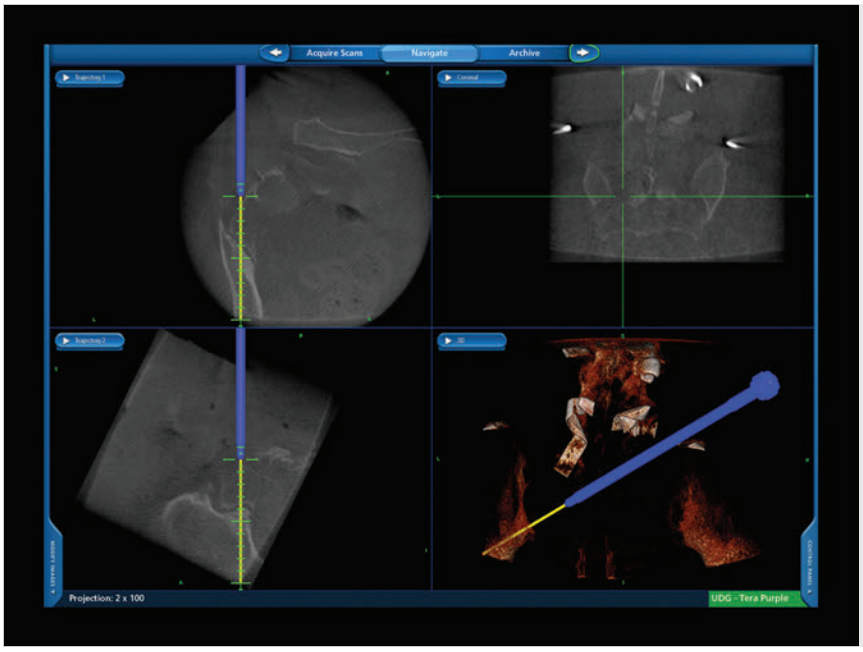

Fig. 71.6 Screen shot of trajectory view for drilling and placement of screw.

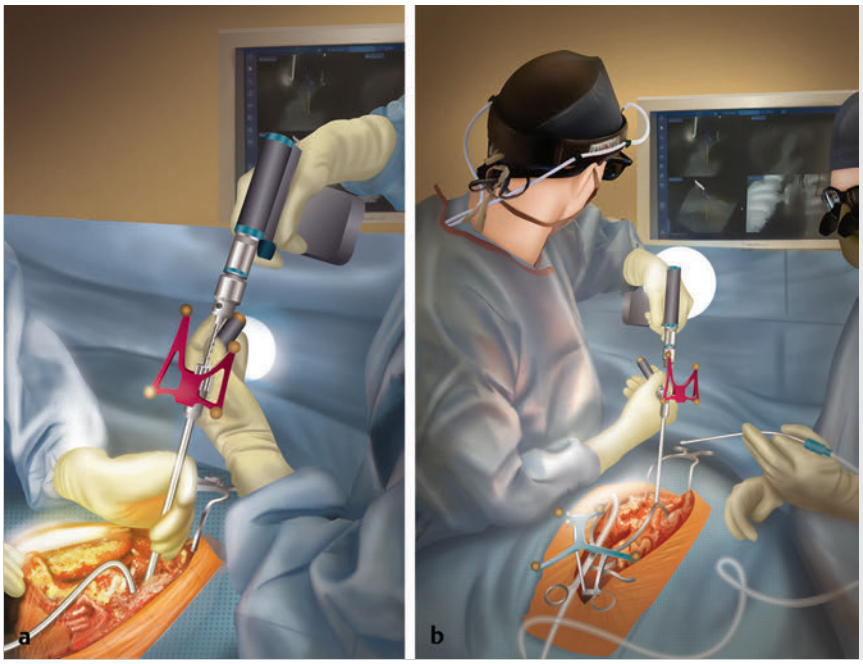

Fig. 71.7 **(a)** Use of guide tube and power drill (**b**) while watching the advancement on navigation screen.

Section XIV

Pain Management

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XIV

72 Cervical Selective Nerve Root Block via Transforaminal Injection

Lisa Marino

72.1 Description

A cervical selective nerve root block is a fluoroscopically guided diagnostic injection in which the cervical spinal nerve is individually anesthetized with local anesthetic.

72.2 Key Principles

Diagnostic selective nerve injections are used to help determine the source of radicular pain when it is otherwise unclear. Cervical radicular pain may not follow the classic dermatomal patterns and therefore can make the diagnosis challenging. Additionally, a patient can have multiple areas on imaging that could potentially cause symptoms. Before proceeding with therapeutic interventions such as steroid injections or surgery, it can be valuable to identify the nerve or nerves involved. Diagnostic selective nerve injections can help identify the source of pain.

Diagnostic injections should be carried out at one nerve level at a time and on separate days if more than one nerve is to be tested. The patient should fill out a pre- and postinjection pain diagram to assess if the nerve block improved the symptoms.

72.3 Expectations

A properly executed cervical selective nerve root block should provide symptomatic relief to the patient if the nerve root is the pain generator. The pain relief will usually last for the duration of the type of anesthetic used. Symptoms of numbness and heaviness into the arm can coincide with the nerve block. Soreness and local swelling of the injection site can be expected.

Cervical selective nerve root block validity has a positive predicted value of 91%. It should be noted that the sensitivity and specificity are not well studied because the outcomes of therapeutic interventions are only known for those who experienced positive pain relief from the selective nerve block. No studies have investigated the treatment outcomes for patients with a negative diagnostic block.

72.4 Indications

This procedure is done to define nerve roots involved in cervical radicular pain and ultimately guide treatment to that area.

72.5 Contraindications

Absolute contraindications include the inability to use contrast medium or evidence of local infection. Relative contraindications include anatomical abnormalities that make achieving a safe injection difficult. Blood thinners and antiplatelet agents should be discontinued prior to the procedure.

72.6 Special Considerations

Cervical injections via the transforaminal approach can be potentially dangerous, leading to catastrophic results of spinal cord infarction, vertebral artery dissection, stroke, and death. Therefore, a physician should perform the injection only with extensive training in fluoroscopically guided procedures. Digital subtraction is recommended for added visualization of potential intravascular flow.

72.7 Special Instructions, Positioning, and Anesthesia

The cervical intervertebral foramen anatomy is composed of a floor, a roof, and the anterior and posterior walls. The posterior wall is made of the inferior articular process directed inferiorly from above, the facet joint and the superior articular process directed superiorly from below. The posterior vertebral body forms the anterior wall. The floor is formed by the pedicle of the lower vertebrae and the roof is from the pedicle of the upper vertebrae. The spinal nerves lie along the floor of the foramen and exit just anterior to the superior articular process. The vertebral artery runs vertically outside of the foramen at C2–C6 and typically runs anterior to the exiting nerve, but can be posterior. Radicular arteries can arise from the vertebral artery and anterior cervical artery and lie within the foramen usually anterior to the nerve. The needle should access the foramen posterior to the nerve and anterior to the superior articular process.

Depending on physician preference, the injection can be done with local anesthetic or a twilight anesthesia.

72.8 Difficulties Encountered

Vascular uptake can occur with this injection. If the needle cannot be safely repositioned without vascular uptake, the procedure should be aborted.

72.9 Key Procedural Steps

For proper access to the foramen and fluoroscopic views, the patient can lie in a supine, oblique, or lateral decubitus position depending on physician preference. An oblique and anteroposterior (AP) fluoroscopic view of the cervical spine should be obtainable without the patient moving. The oblique view is correct when the target foramen is at its largest width and height. The needle insertion target is determined in the oblique view at the midportion of the superior articular process that makes up the posterior wall of the target foramen. After the skin is prepped sterilely, a 22-gauge or 25-gauge 1–½-inch needle is inserted into the skin. In the oblique view, the needle is advanced under intermittent fluoroscopic guidance until bone

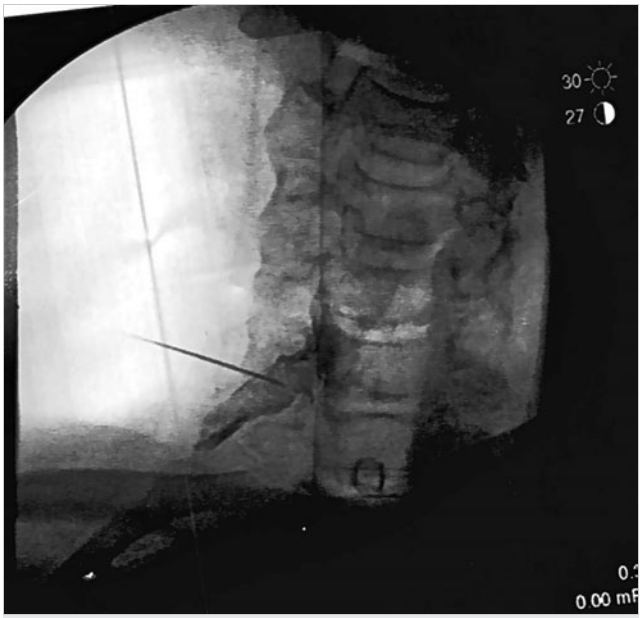

Fig. 72.1 Depicted is a right C7 selective nerve root block via the transforaminal approach. The nerve root is outlined and a small flow of contrast can be seen medial to the pedicle.

of the superior articular process is abutted to gauge depth. In the AP view, the needle is angled to just slip off the superior articular process anteriorly and is incrementally advanced under fluoroscopy just lateral to the horizontal line bisecting the articular pillars. A small-volume extension tubing is attached to the needle and contrast medium is injected. To make the injection a selective nerve root block and not an epidural injection, the physician must monitor the amount of contrast dye injected under live fluoroscopy (see **Video 72.1**). The flow of the contrast should cover the nerve and begin to flow medially through the foramen to the uncinate process (see ▶ Fig. 72.1—right C7 selective nerve root outline). When the volume of contrast begins to flow into the epidural space it should be noted. Local anesthetic equal to the volume of contrast medium needed to cover the nerve and just before the flow into the epidural space is injected. A typical volume is 0.3 to 0.5 mL of lidocaine 2% or 4% or bupivacaine 0.5%.

Steroids can then be injected after the local anesthetic, but doing so will convert the procedure to a therapeutic injection, no longer making it a diagnostic block. Any anesthetic flowing into the epidural space, either by the steroid or a larger than necessary volume, can spread to segmental structures and compromise the integrity of the nerve root block.

72.10 Bailout, Rescue, and Salvage Procedures

If any intravascular uptake is noted on live fluoroscopy or digital subtraction, the injection should be aborted.

Pitfalls

- Inadvertent intravascular injection of local anesthetic can cause adverse events of spinal anesthesia that may lead to respiratory compromise and seizures.
- The patient will need to be supported until the anesthetic wears off.
- Intravascular injection of steroids can have catastrophic results of paralysis, stroke, and death; therefore, use of a nonparticulate steroid such as dexamethasone is recommended to lessen the potential risk.

73 Atlantoaxial Joint Injection Technique

Zach Broyer

73.1 Description

The atlantoaxial joint is the proper terminology for the C1–C2 joint. The joint slopes caudally and laterally and because it is a synovial joint, arthritis and inflammation can occur. The vertebral artery runs along the lateral aspect of the joint and the sensory C2 nerve travels through the midpoint of the joint.

73.2 Key Principles

Patients may have normal X-rays, magnetic resonance imaging (MRI), or computed tomography (CT) scans of the C1–C2 joint, but can still have pain emanating from this structure. Therefore, a careful history, physical exam, and atlantoaxial injections are used to make the diagnosis of atlantoaxial joint pain or cervicogenic headache. Occipital or suboccipital headaches may also be related to the C2/3 facet joint or the C2/3 intervertebral disk, or they may be related to myofascial pain from the upper trapezius musculature. The atlantoaxial joint allows for 70 degrees of lateral rotation around the odontoid process and 5 degrees of flexion and 10 degrees of extension at the joint. The clinical presentation of headaches cannot be specifically localized by physical exam and history to the C1–C2 joint, although it is thought that occipital pain, focal tenderness in the area below the occiput, and pain on rotation of the C1–C2 joint or passive motion of C1 may be indicative of lateral atlantoaxial joint pain. The gold standard in diagnosis is a diagnostic block of the lateral atlantoaxial joint.

73.3 Expectations

Diagnostic blocks are used to prove that the joint is the cause of the patient's pain and headaches. Once diagnosed, treatments like radiofrequency ablation or surgery can be done to give the patient long-term relief. Therapeutic injections with steroids can be utilized for short-term patient benefit.

73.4 Indications

Patients with cervicogenic headaches are usually associated with arthritic changes at the C1/2 joint. Patients must be ruled out for other causes of headache due to the inability to localize the C1–C2 joint on physical exam.

73.5 Contraindications

Patients with contrast allergies cannot safely undergo a contrast injection. An inability to use contrast would allow for improper visualization of a potential intravascular injection. The use of live fluoroscopy with iodinated contrast agents is necessary to ensure patient safety and prevent negative outcomes. Patients on anticoagulation therapy should also not undergo the procedure unless the prothrombin time or international normalized ratio can be normalized; this is done to minimize the possibility of hematoma formation, which would require surgical evacuation.

73.6 Special Considerations

Patients with contrast allergies cannot safely undergo the procedure.

73.7 Special Instructions, Positioning, and Anesthesia

Injection of the lateral atlantoaxial joint is done using a posterior or anterior approach. The patient lies prone for the procedure on the fluoroscopy table with a pillow underneath the chest and with the forehead supported and the mouth clear to allow for opening of the mouth for better visualization if necessary. The head is placed in mild flexion to allow for better visualization of the joint. The posterior arch of the Atlas image must be adjusted so it does not overlie the target point of the joint (▶ Fig. 73.1, ▶ Fig. 73.2).

73.8 Tips, Pearls, and Lessons Learned

The use of live fluoroscopy with iodinated contrast agents is necessary. Live fluoroscopy with or without digital subtraction allows for visualization of vascular uptake of the contrast agent. If a therapeutic injection with steroid is indicated, a

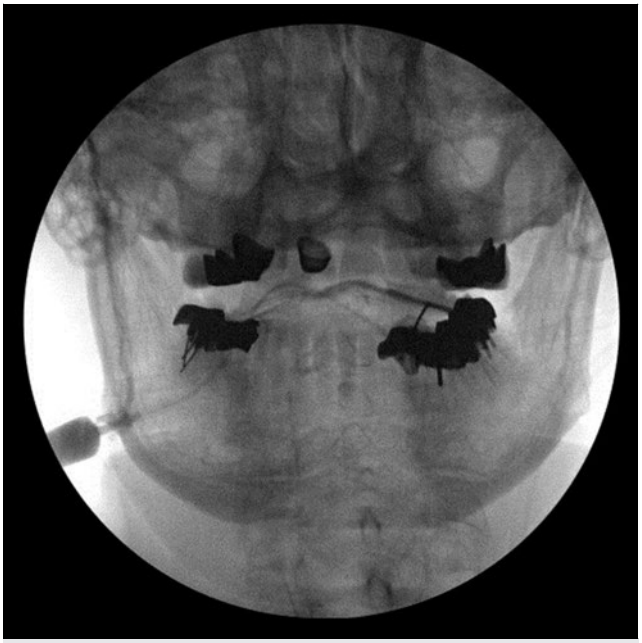

Fig. 73.1 Anteroposterior view. Postcontrast injection image of the atlantoaxial joint with medial joint and contralateral joint spread.

Fig. 73.2 Lateral view. Postcontrast injection image of the atlantoaxial joint with spread confined to the joint.

nonparticulate steroid should be used because it is deemed to be safer in the event of an intravascular injection. Particulate steroids have been associated with negative outcomes in cervical procedures, including ischemic stroke in atlantoaxial joint injection.

The anatomy of the lateral atlantoaxial joint includes the C2 nerve in the middle aspect of the joint and vertebral artery lateral to the joint. These structures need to be avoided during injections; therefore, procedural intervention requires needle placement in the lateral posterior third of the joint.

73.9 Difficulties Encountered

- Improper visualization of the joint under fluoroscopy due to oral implants
- Vascular uptake requiring repositioning of the needle

73.10 Key Procedural Steps

The skin is marked with a marking pen behind the lateral third of the joint and then cleaned with aseptic technique. After the skin is anesthetized with local anesthetic, a 22- or 25-gauge 3–½-inch spinal needle is directed in a posteroanterior approach towards the joint. By aiming for this location one avoids the C2 nerve and ganglion that run directly in the midpoint of the joint. One must contact the bone to determine the distance and depth to the joint for patient safety. This prevents the needle from passing anteriorly through the joint and injuring anterior cervical structures. Once the bone is contacted, the fluoroscopy beam should be directed to the lateral view. This will confirm the needle to be at the posterior aspect of the lateral mass of the atlantoaxial joint. The beam is then redirected into a posterior anterior approach and the needle is withdrawn slightly and directed into the joint at the lateral third of the joint. The needle is slowly reinserted into the joint until it is either felt to be penetrating the joint capsule or has been inserted a few millimeters more than the depth of the posterior aspect of the bone. This should be confirmed with a lateral view. A joint arthrogram is done using 0.3 to 0.5 ML of contrast under live fluoroscopy. Once the needle placement has been confirmed, local anesthetic injection can be done for diagnostic blocks and local anesthetic with nonparticulate steroid can be done for the therapeutic injection (**Video 73.1**).

73.11 Bailout, Rescue, and Salvage Procedures

Radiofrequency ablation can be done, but this typically would require proof that the pain is related to the C1–C2 joint by a local anesthetic injection.

Pitfalls

- Vascular uptake may occur, requiring readjustment of the needle to prevent injection of steroid into the vasculature.
- If the needle traverses medial to the joint, catastrophic injury by injection of the needle into the spinal cord may occur.

74 Lumbar Transforaminal and Interlaminar Epidural Steroid Injection

Jeremy Simon, Steven Derrington, and Joshua Armstrong

74.1 Description

The placement of corticosteroids for the treatment of lumbar radiculopathy is a commonly used nonoperative treatment. Three ways to access the lumbar epidural space may be utilized: (1) Caudal technique: A spinal needle is advanced through the sacral hiatus to below the filum terminale at S2 (▶ Fig. 74.1). (2) Interlaminar technique: A Tuohy needle is advanced between the laminae, engaging the ligamentum flavum. A syringe is used with air or saline and resistance is felt when the needle is within the ligament. Loss of resistance is felt when the needle accesses the posterior epidural space (▶ Fig. 74.2). (3) Transforaminal approach: A spinal needle is advanced in an oblique angle on a trajectory above or below the exiting painful spinal nerve (▶ Fig. 74.3). See Videos 74.1 and 74.2 for a demonstration on how these procedures are performed.

74.2 Key Principles

A thorough history and physical are critical in proper patient selection. Patients with signs and symptoms of cauda equina syndrome or progressive neurologic deficits should be referred for spine surgery. Patients with bleeding disorders or on anticoagulants must have their clotting factors normalized prior to performing the injection. Risk and benefit must be weighed in these circumstances and clearance from a physician managing the condition should be obtained.

The use of fluoroscopy in any of the techniques significantly improves safety and accuracy in the use of these procedures. Although the incidence of complications with these procedures is relatively low, they can be catastrophic. Reports of paralysis from lumbar transforaminal injections are reported at multiple levels. Recent data suggest using low or nonparticulate steroid preparations to reduce the chance of inadvertent injection into

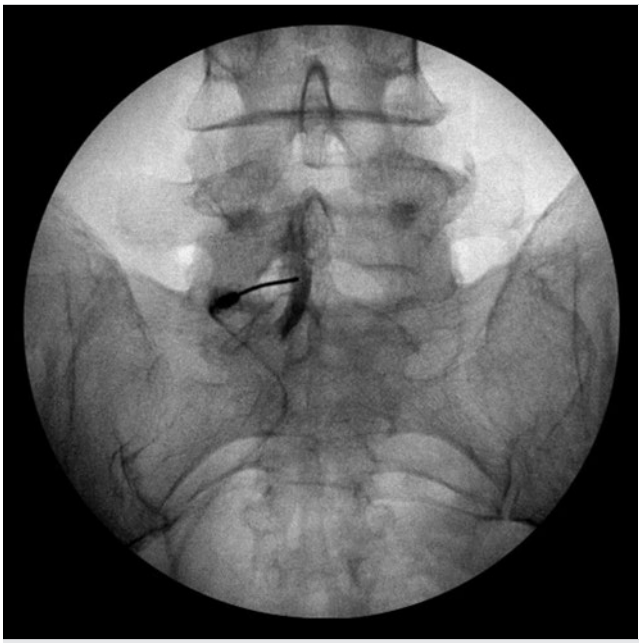

Fig. 74.2 Left L5–S1 interlaminar epidural injection.

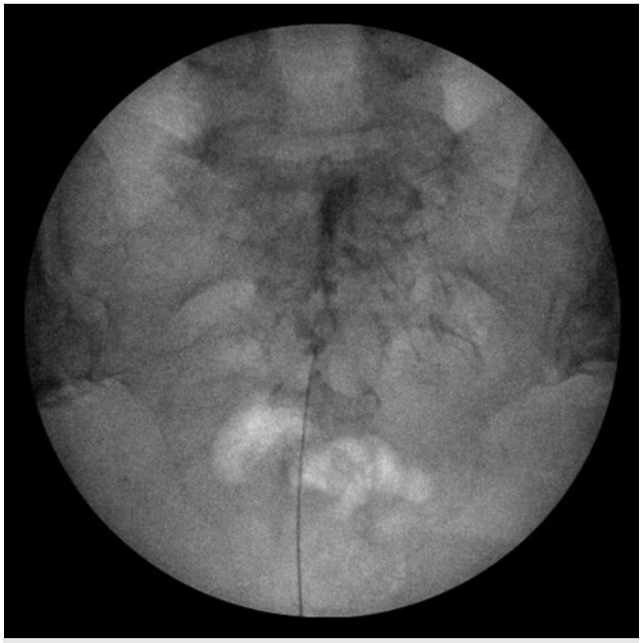

Fig. 74.1 Caudal epidural injection.

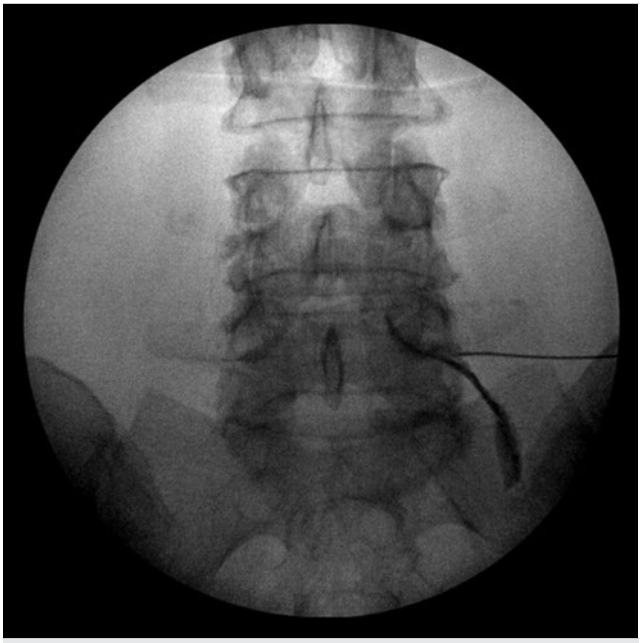

Fig. 74.3 Right L5 transforaminal epidural steroid injection.

a vessel with communication to the spinal cord. See Videos 74.1 and 74.2 for a demonstration of how these procedures are performed.

74.3 Expectations

Patients should be counseled that the purpose of the epidural steroid injection is to reduce inflammation and radicular pain associated with the underlying pathology. Assumptions that the steroid injection will reduce the size of the disk herniation or aid in the healing process are unsubstantiated. The favorable natural history of disk herniations with or without interventions should be reinforced; therefore, the epidural is offered as part of pain control in a nonsurgical scenario. Many studies have demonstrated at least short-term efficacy for chronic or relapsing radiculopathy.

74.4 Indications

Epidural steroid injections are indicated in the treatment of benign compressive painful lumbar radiculopathy secondary to a herniated nucleus pulposus and spinal stenosis. Consideration may be given to patients with these conditions who fail a trial of physical therapy and anti-inflammatory medications or when these interventions are not feasible.

74.5 Contraindications

Patients with progressive neurologic deficits should be referred to the surgeon in lieu of an epidural injection. Patients with active or local-site infections are not candidates for epidural steroid injections. Interlaminar epidurals may not be performed at a level of previous surgery where there is removal or significant disruption to the ligamentum flavum. Patients with significant medical comorbidities requiring anticoagulation are a relative contraindication as the risk of bleeding is increased. Uncontrolled or poorly controlled diabetes mellitus is a potential contraindication and coordination with the treating physician is essential.

74.6 Special Considerations

Patients with difficulty lying prone can be injected with the use of conscious sedation. The use of pillows under the abdomen to create a flexion moment in the spine often helps stenosis patients to lie flat more comfortably. Patients with iodine allergy should be premedicated with prednisone, H2 blockers, and diphenhydramine. Intravenous access, monitoring, and a crash cart including epinephrine should be available in the injection suite.

74.7 Special Instructions, Positioning, and Anesthesia

In experienced hands, epidural injections are quick and normally tolerable without sedation. If conscious sedation is utilized, the patient should not eat or drink for 8 hours prior to the injection. Patients are placed in the prone position on a radiolucent table. Local anesthetics such as lidocaine 1% or bupivacaine 0.25% are typically used. If a patient is difficult to position due to pain or has significant anxiety with the procedure, conscious sedation with midazolam, fentanyl, propofol, or ketamine is often employed. A skilled anesthesiologist or nurse anesthetist must be present for these cases and the patient's airway and vital signs, including pulse oximetry, must be continuously monitored during the procedure.

74.8 Tips, Pearls, and Lessons Learned

A good skin wheel is helpful in making the initial needle placement comfortable for the patient. Intermittent injection of local anesthetic can help to alleviate pain with needle placement in deeper tissues. The use of extension tubing during live contrast injection helps reduce radiation exposure to the physician's hands and gives a clearer picture. Injection of the steroid solution through an extension tube also reduces the pressure as the medication is administered, normally making the procedure less painful. Prior to injection, confirmation of the correct level, pain location, and correlation of magnetic resonance imaging (MRI) with the plain films is essential. Reviewing the plain films for transitional anatomy and the MRI or computed tomography (CT) scan for the location of neural compression is paramount to successful outcomes.

74.9 Difficulties Encountered

Obesity creates logistical procedural problems in both positioning and image clarity. A lateral picture may be unclear and difficult to interpret in this population. Use of a sterile C-arm cover helps to avoid inadvertently touching the needle or the gloved hands with the image intensifier. Obese patients may create more radiation scatter, as larger amounts of X-ray are needed to penetrate their soft tissues. Use of intermittent fluoroscopy and stepping away from the source on the C-arm help to reduce the physician's radiation exposure. Anxious patients or those in tremendous pain may be difficult to treat because of movement. Reassurance and generous use of local anesthetic with the least amount of needle manipulation are helpful. If they cannot remain still or it is too painful, sedation can be considered.

74.10 Key Procedural Steps

The patient is placed in the prone position and sterilely prepped after informed consent is signed and all the patient's questions are answered. Vital signs are monitored prior to, during, and after the procedure.

For a lumbar transforaminal injection, the proper level is confirmed by spot anteroposterior pictures and lateral pictures, if necessary. The C-arm is then angled obliquely approximately 30 to 45 degrees ipsilaterally to the side of the injection and the vertebral end plates aligned, showing the classic "scotty dog" picture. A sterile, fenestrated drape or towel is placed over the target area. The soft tissues overlying this area are anesthetized with 3 to 5 cc of 1% lidocaine or 0.25% bupivacaine without

epinephrine. A 22-gauge spinal needle of the appropriate length for patient body habitus is placed in line with the image intensifier and directed "under the chin of the scotty dog" to the superior aspect of the neural foramen. The needle is advanced to contact the transverse process and then an anteroposterior (AP) picture is obtained. The needle should not violate the "six o'clock position" of the pedicle, imagining the pedicle as a clock face. A lateral picture then confirms correct needle depth, which is the posterior third of the neural foramen. Live injection of nonionic iodinated contrast is used to confirm epidural flow of medication and confirm the absence of vascular or intrathecal spread. After confirmation of the proper flow of contrast, the therapeutic injectate is administered.

The interlaminar approach is performed with the same setup, but a Tuohy needle and a "loss of resistance" syringe utilized. The interlaminar space is identified under AP visualization and the soft tissues anesthetized as described above. A Tuohy needle is normally placed to the left or right of midline (often to the more painful side). It is advanced to the top of the inferior lamina and then a lateral or contralateral oblique image is used to confirm depth. The needle is then redirected and engaged into the ligamentum flavum. Loss of resistance to pressure confirms epidural placement. A small amount of contrast is injected in the lateral or contralateral view to confirm epidural flow, which appears as a straight line. Live injection in the AP view is used to ensure the absence of vascular flow.

74.11 Bailout, Rescue, and Salvage Procedures

If the dura is punctured inadvertently, the patient may develop a spinal headache. The injection of autologous blood into the epidural space (blood patch) for refractory pain and headaches may significantly reduce this problem.

Pitfalls

- Inadvertent injection into a blood vessel, especially with particulate steroids, can potentially cause catastrophic neurologic injury.
- Judicious and monitored use of corticosteroid injections should be used in patients with osteoporosis and up-to-date dual-energy X-ray absorptiometry (DXA) scans obtained.

75 Sacroiliac Joint Injection Technique

Ari Greis

75.1 Description

Intra-articular joint injections with corticosteroids have long been a way of managing pain and inflammation in patients with degenerative joint and rheumatologic disease. The sacroiliac (SI) joint is susceptible to osteoarthritis, inflammatory arthritis, and mechanical pain related to abnormal joint mechanics. Due to the SI joint's complex anatomy and position in the pelvis, an intra-articular joint injection cannot be reliably performed without the assistance of image guidance. The most common way to perform an SI joint injection is with fluoroscopic guidance.

75.2 Key Principles

The SI joint is a potential source of low back, buttock, groin, and lower extremity pain. It is estimated to be the cause of 15 to 30% of cases of low back pain. The actual prevalence of SI joint-mediated pain may be overestimated as most of the studies looking at its prevalence focus on patients already suspected of having SI joint pain. The diagnosis of SI joint-mediated pain is complicated by the joint's proximity to other potentially painful structures in the low back, such as the lower lumbar intervertebral disks and facet joints. Because physical examination and imaging studies fail to reliably confirm SI joint pain, intra-articular SI joint injections are considered the gold standard for confirming the diagnosis. It is important to recognize that some patients may have extra-articular joint pain arising from gluteal tendon enthesopathy, fractures, and ligamentous injuries.

Because proper needle placement into the SI joint greatly affects outcomes, image guidance is recommended. Sacroiliac joint injections are most commonly done with fluoroscopic guidance; however, computed tomography (CT) and ultrasound are sometimes used as well. In a review of the data on efficacy of intraarticular SI joint injections, most studies show that an image-guided SI joint injection can provide good pain relief from 6 months to a year.

75.3 Expectations

The purpose of an intra-articular SI joint injection is the temporary reduction in joint inflammation and pain. Patients should understand that the amount and duration of pain relief is unpredictable and may vary greatly from person to person. The hope is that a corticosteroid injection can help facilitate the goals of a more comprehensive rehabilitation program including therapeutic exercise.

75.4 Indications

The initial treatment of SI joint-mediated pain consists of relative rest, anti-inflammatory medications, and physical therapy. Patients with refractory SI joint pain who have failed more conservative measures are candidates for an intra-articular steroid injection. In addition, patients with acute pain that interferes with activities of daily living, sleep, and/or the ability to participate in a therapeutic exercise program can be considered for injection therapy.

75.5 Contraindications

Any patient with presumed SI joint-mediated pain that has a progressive neurologic deficit in the lower limb or changes in bowel or bladder function should be worked up with advanced imaging of the spine before proceeding with injection therapy. It is also important to rule out other potential causes of SI joint pain including traumatic or insufficiency pelvic fracture and rarely cancer. Patients with an active infection should avoid joint injection therapy. Patients on anticoagulation medications are at increased risk of bleeding with SI joint injections. It is important to discuss the risks of both performing an injection while on anticoagulants versus the risk of having a cardiovascular event while off the medications. Uncontrolled diabetes mellitus is also a contraindication to any corticosteroid injection and coordination with the patient's treating physician is imperative to ensure the proper management of hyperglycemia that occurs after steroid injections.

75.6 Special Considerations

Patients with an allergy to shellfish, iodine, or contrast dye should be premedicated with a combination of oral prednisone, diphenhydramine, and an H2 blocker. Due to the possibility of an allergic reaction or vasovagal event, all injection suites should have equipment for intravenous access, vital sign monitoring, and a crash cart with appropriate medications available.

75.7 Special Instructions, Positioning, and Anesthesia

Patients who have difficulty lying in the prone position may benefit from a pillow under their lower abdomen and/or pelvis. Sacroiliac joint injections are typically done without sedation. Some patients may report extreme needle phobia or significant pain and/or anxiety about the procedure and can thus be treated by an anesthesiologist with some combination of midazolam, fentanyl, and propofol for conscious sedation during the injection. These patients should not eat or drink anything for at least 8 hours before the injection.

75.8 Tips, Pearls, and Lessons Learned

Local anesthesia combined with sodium bicarbonate can reduce the burning sensation associated with the initial needle stick and skin wheel. Additional local anesthetic in the deeper soft tissues throughout the procedure can also reduce pain levels while proper needle placement is performed. Extension tubing

can be used while injecting contrast dye under live fluoroscopy to reduce the physician's exposure to radiation.

75.9 Difficulties Encountered

Calcified posterior SI joint ligaments and the SI joint's interlocking ridges can sometimes make it difficult to advance the needle past the posterior aspect of the sacrum. Repositioning the C-arm and attempting the injection more cephalad to the inferior SI joint is recommended. Obesity makes patient positioning more difficult and reduces the quality of fluoroscopic images. Longer needles are required and sometimes a sterile C-arm cover is necessary to prevent inadvertent touching of the physician's hand or needle to the C-arm.

75.10 Key Procedural Steps

- The patient lies prone on an adjustable radiolucent table.
- In anteroposterior (AP) fluoroscopic projection, the medial SI joint is formed by the posterior joint articulation.
- The C-arm is rotated contralaterally until the medial cortical line of the posterior articulation is in focus. A slight cephalad tilt of the C-arm can sometimes help the physician differentiate the anterior and posterior articulations.
- The skin is cleaned with an antiseptic and dressed with a sterile drape.
- The skin is anesthetized and needle puncture is performed 1 to 2 cm superior to the lower edge of the SI joint at the level of the zone of maximal radiographic translucency.
- The needle is advanced keeping the hub and tip in line with the radiographic beam and aiming for the translucent portion of the SI joint image. Penetration of the SI joint is characterized by a change in resistance. The needle tip may appear slightly curved between the os sacrum and os ilium. On a lateral view, the needle tip should appear anterior to the dorsal edge of the sacrum and preferably in the anterior half of the SI joint.
- Injection of 0.25 to 0.5 mL of contrast agent should show dispersal along the articulations and filling of the inferior joint capsule (▶ Fig. 75.1).
- The injectate is administered, usually containing 1 cc of local anesthetic and 1 cc of corticosteroid.
- **Video 75.1** shows the key steps to the SI joint infection

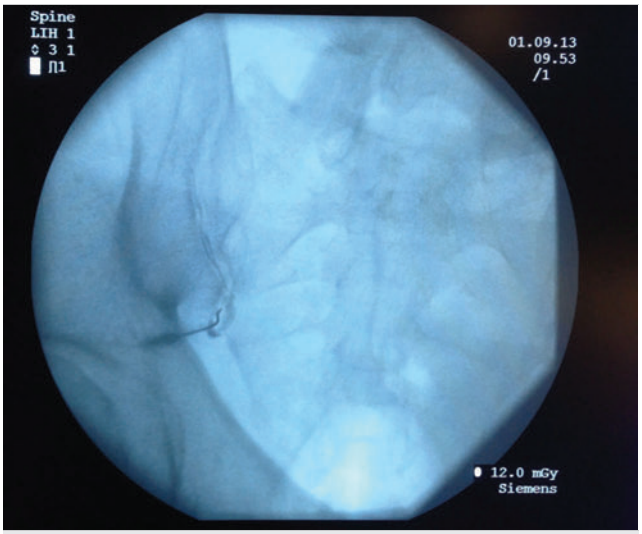

Fig. 75.1 Fluoroscopic image of sacroiliac joint injection with contrast dye.

75.11 Bailout, Rescue, and Salvage Procedures

If an intravascular contrast dye pattern is seen after multiple attempts to reposition the needle within the SI joint, the procedure should be aborted.

Pitfalls

- The inadvertent injection of particulate corticosteroids into a blood vessel has been associated with catastrophic neurologic injury during lumbar epidural steroid injections.
- Although occasional vascular uptake is seen on contrast dye images during SI joint injections, the pelvic vasculature does not feed the spinal cord like some lumbar arteries do. Sacroiliac joint injections with corticosteroids, like other forms of exogenous steroid administration, such as epidural steroid injections, may lead to increased bone fragility and vertebral body fractures in patients who are at risk for osteoporosis. Monitoring of bone density with up-to-date dual-energy X-ray absorptiometry (DXA) scans is recommended.

Section XV

Patient Safety

76 Techniques for Minimizing Radiation Exposure during Fluoroscopy Procedures *288*

77 Effective Use of Neuromonitoring during Spinal Deformity Surgery *292*

XV

76 Techniques for Minimizing Radiation Exposure during Fluoroscopy Procedures

William Ryan Spiker

76.1 Description

Minimizing radiation exposure to the patient, surgical team, and surgeon is critical as the use of intraoperative imaging techniques continues to grow. Intraoperative fluoroscopy is a powerful tool that can minimize the variation in pedicle screw placement, confirm fracture reduction, and evaluate deformity correction. It also has made many minimally invasive spine surgeries possible by allowing percutaneous placement of pedicle screw and rod constructs as well posterior or laterally placed interbody cages and grafts (extreme lateral interbody fusion, lateral lumbar interbody fusion, posterior lumbar interbody fusion, transforaminal lumbar interbody fusion). However, increased radiation exposure to the patient, surgical team, and surgeon has paralleled the growth in intraoperative fluoroscopy. Some studies have shown that in minimally invasive spine surgeries, surgeon exposure is up to 20 times greater than in conventional open spine surgery.

76.2 Key Principles

The United States Nuclear Regulatory Committee has codified the single most important concept in minimizing radiation exposure as ALARA: "As low as reasonably achievable." When applied to spine surgery, this concept can be broken down into four main principles: decreasing exposure time, increasing distance from exposure, shielding, and contamination control.

To decrease exposure time, it is critical to think before you shoot. By making reasonable estimates about the desired location and angulation of the image, you can significantly reduce the number of images required to visualize the desired anatomy. For example, when evaluating the L5/S1 disk space or the L5 pedicles, place the C-arm at a reasonable craniocaudal level based upon the posterior-superior iliac spine or the iliac crest and allow for appropriate angulation to match the patient's lordosis. Use of a mounted laser site on the fluoroscopy unit can further guide appropriate placement and minimize unnecessary images and radiation.

It is important to move as far away from the fluoroscope as possible, doubling your distance from a source of radiation decreases your exposure by a factor of 4. Thus, at a 90-degree angle from a fluoroscopic beam a surgeon's exposure at 3 feet is approximately 0.1% of the radiation at the center of the beam and at 6 feet it is 0.025%. Simple maneuvers to increase the distance between yourself and the image intensifier include stepping away when able and keeping your hands out of the field (use a long Kocher clamp if necessary): Remember that 6 inches is twice as far away as 3 inches.

Appropriate shielding in the operating room (OR) includes the use of lead gowns, thyroid shields, and lead glasses. The amount of dose attenuation afforded by lead aprons and thyroid shields ranges from 90 to 99% depending on the thickness of the lead used (.25–.5 mm) (▶ Fig. 76.1). Lead glasses reduce the radiation dose to the cornea by approximately 30 to 70%. Contamination from holes or cracks in lead aprons and leakage from the X-ray generator can add up to significant radiation exposure. The C-arm and lead aprons should be tested annually to minimize this effect.

76.3 Expectations

When using appropriate techniques for intraoperative fluoroscopy, one can expect to decrease the amount of radiation exposure to the patient, the surgical team, and the surgeon. Further, these techniques avoid any compromise of surgical precision or patient safety.

76.4 Indications

Radiation exposure should be minimized whenever any intraoperative imaging modality is used (fluoroscopy, radiographs, or intraoperative computed tomography [CT] scan). The potential to minimize exposure is greatest with fluoroscopy because often many images are taken, and some images require the surgeon to be relatively close to the radiation source. Both radiographs and intraoperative CT scans allow the surgeon to move to a shielded location to nearly completely block any radiation exposure.

76.5 Contraindications

The only contraindication to minimizing radiation exposure is in the setting of an emergency, such as a vascular injury or anesthesia issue requiring immediate completion of a certain portion of the case. In this situation, fluoroscopy technique should be focused on minimizing the surgical time and not on minimizing the radiation exposure.

76.6 Special Considerations

Minimizing radiation exposure to the patient and surgical team is complicated by patient factors such as obesity and spinal deformity (scoliosis). In the case of obesity, the increased tissue surrounding the spine can make visualization difficult. Centering the area of interest in the image and coning the beam to a smaller diameter can help clarify local anatomy. Occasionally, higher doses of radiation must still be used to adequately visualize the structure of interest. In the presence of a significant spinal deformity such as scoliosis, the orientation of the C-arm must be modified at nearly every level to allow adequate visualization on both anteroposterior (AP) and lateral images. Lateral images should be checked to ensure that the pedicles overlap completely and the superior and inferior end plates appear as a single line, while the AP images must be confirmed to have the spinous process centrally located between the pedicles with a

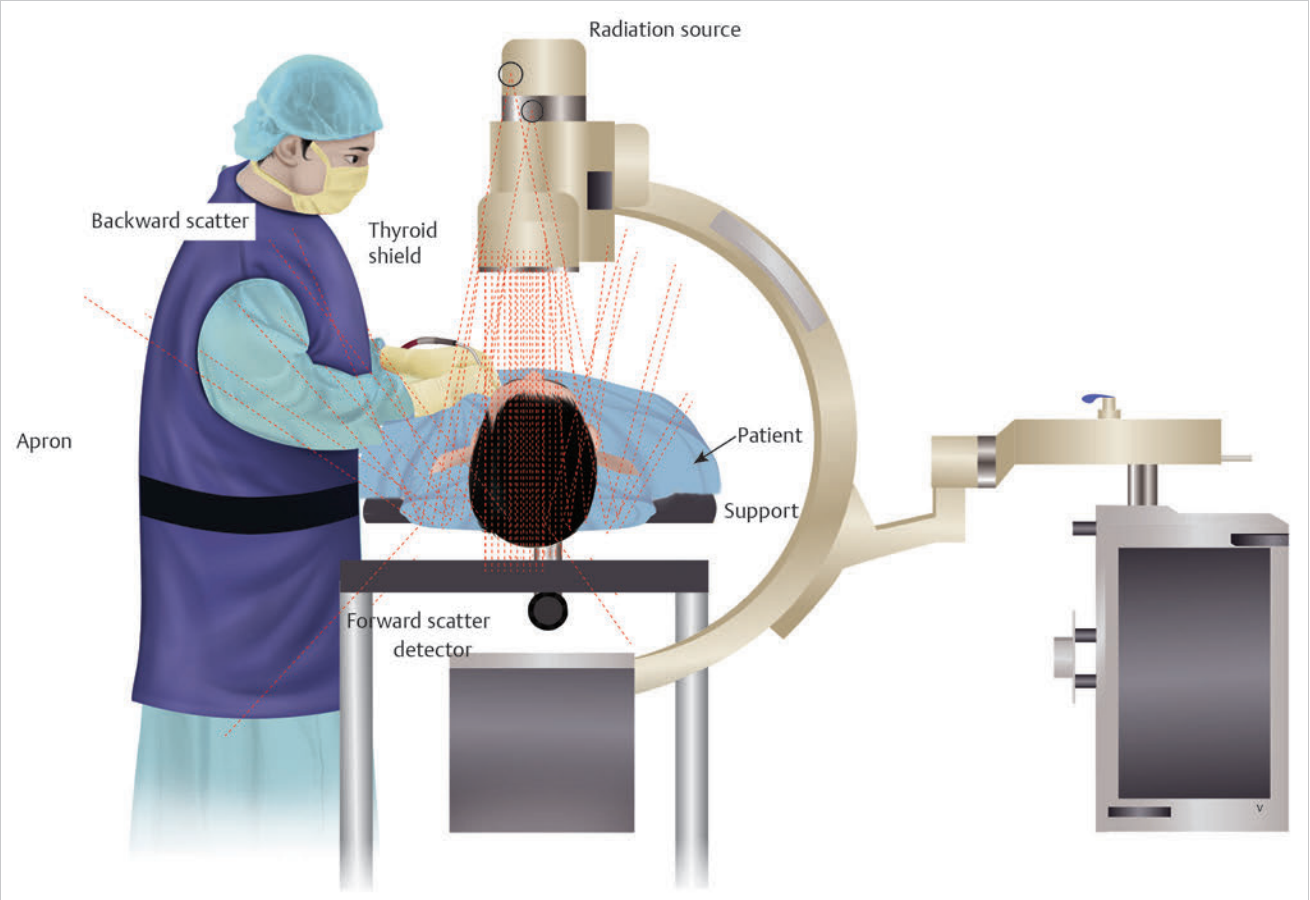

Fig. 76.1 This diagram identifies the basic components of the C-arm and demonstrates that the highest amount of radiation scatter occurs on the side of the radiation source.

single line representing the end plates (▶ Fig. 76.2). An understanding of the three-dimensional curve can help the surgeon guide appropriate C-arm placement for these images as the technician moves up or down the spine.

76.7 Special Instructions, Positioning, and Anesthesia

Thoughtful patient positioning is critical to obtaining adequate intraoperative fluoroscopic images. When positioning for a cervical spine case (anterior or posterior), gentle downward traction should be placed on bilateral shoulders with thick (3 inch) silk or cloth tape to visualize the lower cervical spine. For posterior thoracolumbar cases, the hands should be placed above the head with the shoulders and elbows at approximately 90-degree angles. In all cases, the electrocardiogram leads, neuromonitoring wires, and all other tubing should be moved out of the path of any potential intraoperative images.

Prior to beginning the case, communicate with the technologist in the room to make sure he or she understands the procedure to be performed and the goals of imaging. When obtaining images, minimizing background noise in the room by turning down the music and keeping peripheral conversations to a minimum allow improved communication with the C-arm technologist.

76.8 Tips, Pearls, and Lessons Learned

The key concept to keep in mind when using fluoroscopy is ALARA–as low as reasonably achievable. This mantra can be boiled down to four tenets: (1) Decreasing exposure time, (2) increasing your distance from radiation, (3) appropriate shielding, and (4) controlling contamination sources.

76.9 Difficulties Encountered

One rarely discussed complication of intraoperative fluoroscopy is the potential for contamination of the sterile field. Proper sterile draping of the C-arm should be taught to all OR staff and directly monitored by the surgeon. When obtaining images, the wound should be filled with sterile fluid and covered with a sterile towel to both enhance image quality and decrease potential contamination. The surgeon should change his or her gloves after any manual manipulation of the C-arm. Further, whenever in doubt the C-arm should be redraped rather than risk contamination of the sterile field.

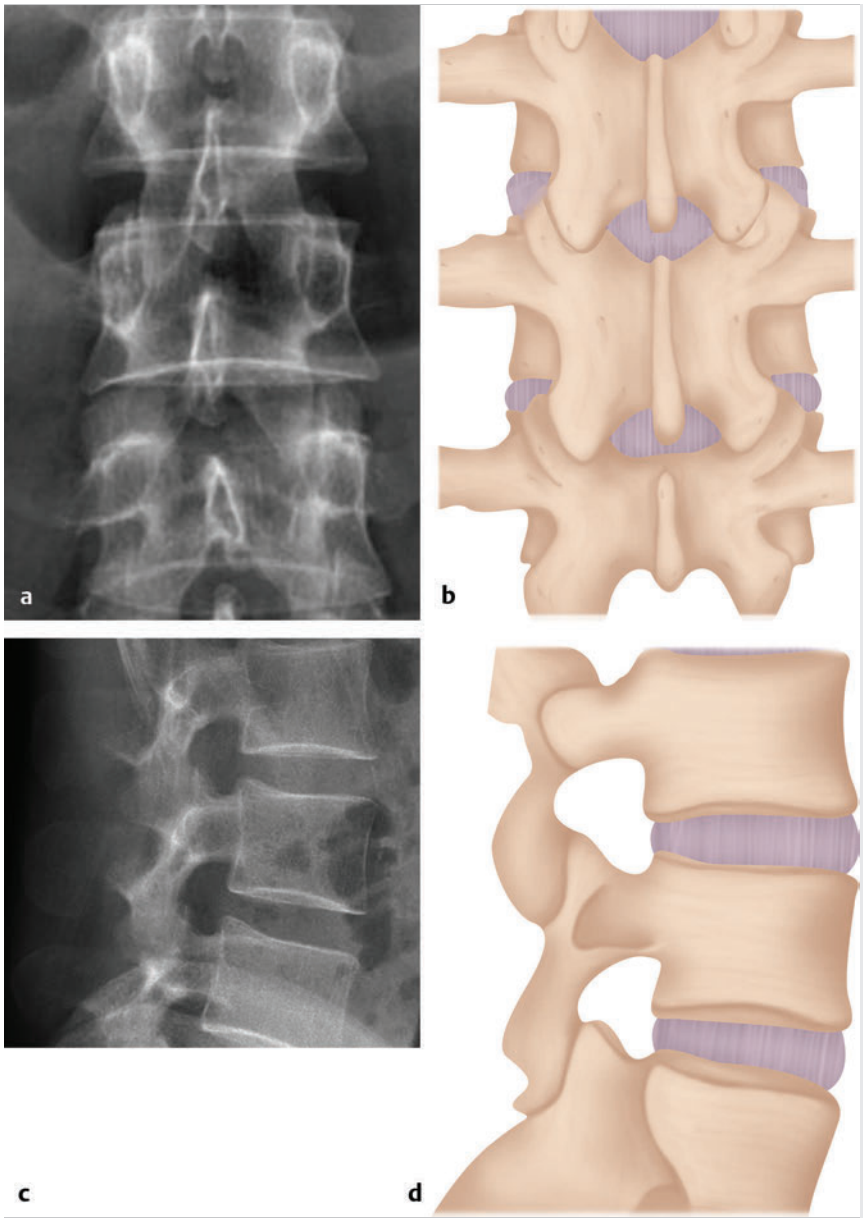

Fig. 76.2 (a,b) An acceptable anteroposterior (AP) image of a lumbar vertebral body should have a midline spinous process centered between symmetric pedicles with a single radiodense line along the superior and inferior end plates. **(c,d)** An acceptable lateral image of a lumbar vertebral body should show single radiodense lines representing the superior and inferior cortical border of the pedicles, the posterior border of the vertebral body, and the superior and inferior end plates.

76.10 Key Procedural Steps

Proper fluoroscopy use begins with the setup (**Video 76.1**). The C-arm should be easily maneuverable without impeding wires, intravenous lines, or cords; and the display screen should be clearly visible from both sides of the operative site. If using fluoroscopy for incision localization, anatomical landmarks should still be used for guiding the initial estimate of the surgical site. By using landmarks such as the carotid tubercle (C6), the inferior tip of the scapula (T7/T8), and the iliac crest (L4/5), the initial estimate should nearly always be close enough to the desired level to adequately guide incision placement. Marking the location on the floor of the OR of this first image can help guide the fluoroscopy technician when obtaining images later in the case. Intraoperatively, attention must be focused on attempting to get the desired image on the first attempt. When multiple attempts are required, the previous image should be closely examined to guide movement of the C-arm in all three planes to improve the image quality.

76.11 Bailout, Rescue, and Salvage Procedures

When fluoroscopic images fail to be helpful due to body habitus, patient positioning, or technical difficulties, plain radiographs and/or an intraoperative CT scan can often provide additional information. When performing minimally invasive spine surgery and fluoroscopic visualization is inadequate, conversion to an open procedure allows direct visualization of the anatomy in question.

Pitfalls

- One of the most common mistakes is the overuse of live fluoroscopy. This mode can expose the patient and entire surgical team to high doses of radiation in a very short time and should be used only when absolutely necessary.
- Obtaining "scout" images to guide the proper placement of the beam should be minimized by thoughtful C-arm placement.
- Lastly, significant changes should be made between each image to minimize unnecessary "repeat" images.
- When it comes to intraoperative fluoroscopy, remember that perfect is the enemy of good—but you can never accept poor imaging.

77 Effective Use of Neuromonitoring during Spinal Deformity Surgery

Abhijeet Kadam, Paul W. Millhouse, Caleb Behrend, and Alexander R. Vaccaro

77.1 Description

Spinal deformity correction surgery entails a small, but definite risk of injury to the neurologic elements. Both mechanical and vascular etiologies contribute to neurologic complications. Mechanical injury frequently results during the placement of wires, hooks, and pedicle screw instrumentation, as well as with distortion of the spinal cord and nerve roots secondary to application of corrective forces to the spinal column. Vascular etiologies include ischemic injury from prolonged severe intraoperative systemic hypotension (mean arterial pressure < 55 mm Hg) and decreased spinal blood flow due to excessive tensioning or kinking of the local spinal vasculature. Intraoperative neurophysiologic monitoring (IONM) strategies have evolved with the objective of providing real-time feedback on the status of neurologic structures and alerting the operative team of any significant changes developing during surgery. This provides a window of opportunity to identify and prevent or even reverse procedural steps that could potentially cause irreversible neurologic deficits.

77.2 Key Principles

Among the IONM modalities, the following have found widespread clinical application for spinal deformity correction surgery:

- Intraoperative neurophysiologic monitoring for spinal cord function
  - Somatosensory evoked potentials (SSEPs): Monitor the dorsal column medial lemniscal sensory pathway
  - Transcranial electric motor evoked potentials (tceMEPs): Monitor the corticospinal tracts
- Intraoperative neurophysiologic monitoring for nerve root function:
  - Spontaneous / free-running EMGs (electromyograms): Monitor individual nerve roots and corresponding segmental muscle innervations.
  - Stimulus evoked / triggered EMGs (electromyograms): Detect misdirected pedicle screws causing breaches through the medial or inferior pedicle wall.

Neurophysiologic recordings with these techniques are established after anesthesia induction and before commencement of surgery. These baseline measurements serve as the patient's own control for any deviations that may arise later. The neurophysiologic monitoring is then continued throughout the duration of the procedure. Detection of a significant change in waveform patterns compared to the preoperative baseline characteristics constitutes a potential neurologic injury. This data may then be used for planning and executing critical "change-inducing" intraoperative maneuvers.

77.3 Expectations

An appropriate combination of neuromonitoring techniques can be expected to provide a global dynamic assessment of spinal cord and nerve root function and to reduce the incidence of postoperative neurologic deficits in deformity correction surgery.

77.4 Indications

Complex deformity-correction procedures involving segmental instrumentation and vertebral osteotomies for idiopathic and congenital scoliosis, neuromuscular scoliosis, kyphosis correction, and prevention of patient positioning-related peripheral nerve injuries

77.5 Contraindications

- Epilepsy
- Cerebral cortical lesions
- Increased intracranial pressure
- Skull defects
- Cochlear implants
- Deep brain stimulators and cardiac pacemakers

77.6 Special Considerations

The effective use of neuromonitoring requires a team approach with preoperative planning regarding the combination of modalities best employed to suit the type of spinal surgery and the vertebral levels involved. Efficient interdisciplinary communication and coordination among the anesthetists, operating surgeons, and neuromonitoring personnel is required for successful implementation.

77.7 Special Instructions, Positioning, and Anesthesia

Certain anesthetic agents interfere with the acquisition of reliable neuromonitoring signals. Inhalational halogenated compounds and nitrous oxide produce a dose-related reduction in amplitude and increase in latency of cortical SSEPs leading to false-positive findings. Likewise, these agents reduce the effectiveness of cranial stimulation while obtaining tceMEPs. Neuromuscular blocking agents should also be avoided while recording MEPs and EMGs as they inhibit data acquisition, altering the motor end plate function. Total intravenous anesthesia (TIVA) protocols with propofol, and more recently, dexmedetomidine have been developed to circumvent the limitations of inhalational agents.

77.8 Tips, Pearls, and Lessons Learned

77.8.1 Somatosensory Evoked Potentials

Somatosensory evoked potentials check the conduction of the dorsal columns of the spinal cord, but are poor predictors of motor function integrity. Motor pathways are supplied by the anterior spinal artery, and ischemic damage to this vascular territory of the spinal cord may be undetectable with SSEP monitoring.

Somatosensory evoked potentials are recordings of summated signals that enter the spinal cord through multiple segments and then undergo averaging and central amplification. Summation and amplification may mask signals that arise from individual nerve root injuries. Also temporal summation and averaging to provide a quantifiable response causes an inherent delay in data acquisition. Somatosensory evoked potentials require up to 5 minutes to detect change under ideal situations. However, an average delay of even 16 minutes has been reported. This permits a significantly long time interval for irreversible neurologic injury to occur before corresponding SSEP changes become apparent in the monitoring data.

77.8.2 Transcranial Electric Motor Evoked Potentials

This technique involves electrically stimulating the cortical motor areas by electrodes applied to the overlying scalp region. Because continuous transcranial stimulation to elicit and record distal compound muscle action potentials (CMAPs) is not feasible, MEPs provide interval snapshot data of the motor function of the spinal cord. This is in contrast to SSEPs that are continuous recordings. In addition, MEPs have the advantage of providing more direct real-time feedback because no signal averaging is involved.

Tongue bites and lacerations as a result of jaw muscle contraction due to indirect stimulation are among the most common complications with MEP monitoring. This should be prevented with the use of soft spacers inserted between the teeth.

77.8.3 Spontaneous EMGs

Like SSEPs, this modality allows for continuous monitoring and feedback throughout the procedure. However, spontaneous EMGs are sensitive to temperature changes, and false-positive patterns frequently arise following cold saline irrigation or the use of electrocautery in close vicinity to spinal nerve roots.

77.8.4 Stimulus Evoked / Triggered EMGs

Repetitive screw insertions or multiple probe passes in an attempt to properly direct a pedicle screw may result in false-positives on triggered EMGs. This occurs due to diminished pedicle integrity with reduction in electrical resistivity to the applied current.

The presence of blood or soft tissues around the head of the pedicle screw can potentially shunt current away. Also in polyaxial screws, the shaft and the head/crown component are separate entities that may not conduct current as a single unit. In this case, it is recommended that the stimulator probe be applied directly to the top of the screw shaft and not to the head or crown. The material properties of the screw itself also influence interpretation of triggered EMGs. Hydroxyapatite coatings reduce conductive capacity and different current threshold cutoffs may be required for interpretation when using coated screws.

Chronically compressed nerve roots have higher triggering thresholds and often give false negative results with stimulus-evoked EMGs.

77.9 Difficulties Encountered

Existing preoperative motor deficits may significantly hamper the ability to obtain MEPs. Severe myelopathy, obesity, spinal cord tumors, or peripheral neuropathy may make SSEPs unrecordable. Similarly, underlying neuromuscular disorders such as myasthenia gravis, muscular dystrophy, and cerebral palsy also preclude reliable EMG acquisition. Detailed medical history taking and a thorough preoperative neurologic examination of all patients are essential for correctly interpreting intraoperative neuromonitoring findings.

77.10 Key Procedural Steps

77.10.1 Somatosensory Evoked Potentials

Constant current stimulators are applied at sites of mixed peripheral nerves in the upper and lower limbs. These typically include the posterior tibial nerve (ankle) and the peroneal nerve (fibular head) for the lower limb, and the median and ulnar nerves (wrist) for the upper limbs. Recording electrodes are placed over the dorsum of the neck and scalp to measure the positive and negative deflections produced as signals ascend via the somatosensory pathways. These signals then pass through an amplifier and digital averager for summation and enhancement for display on a monitor. The baseline recordings are evaluated in terms of amplitude and latency parameters. An amplitude decline of more than 50% and/or a latency prolongation of greater than 10% compared to the baseline values constitutes a significant change and warrants evaluation for potential neurologic injury (▶ Fig. 77.1).

77.10.2 Transcranial Electric Motor Evoked Potentials

Electrodes are placed on the scalp over certain areas (for example, the C1 and C2 region using the 10 to 20 system for electroencephalographic electrode placement), which roughly overlie the corresponding areas of the motor cortex. A low-output impedance electrical stimulator is used to generate a train of

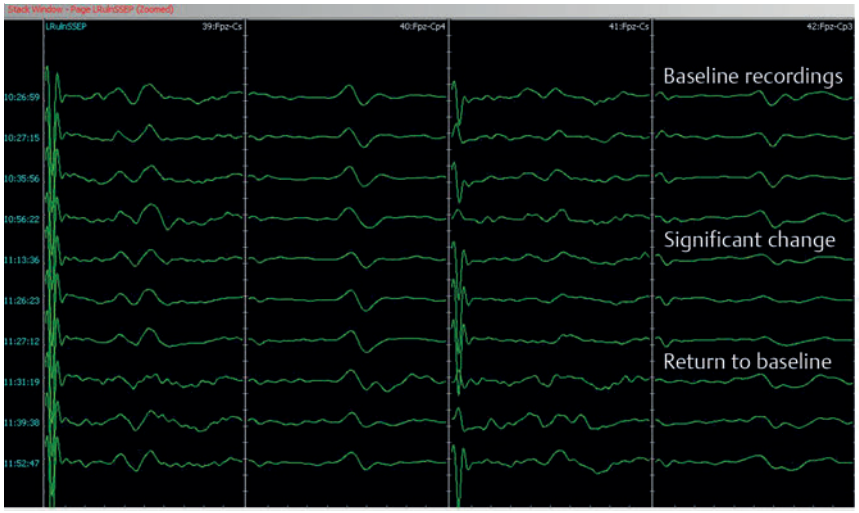

Fig. 77.1 Somatosensory evoked potentials demonstrating variations from baseline in terms of amplitude and latency changes in the wake of potential spinal cord injury or ischemia.

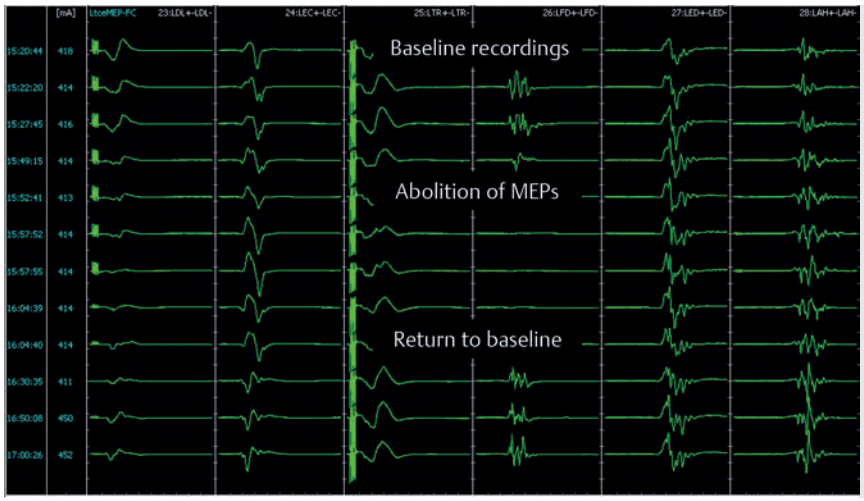

Fig. 77.2 Motor-evoked potential recordings demonstrating near abolition of compound muscle action potentials and subsequent return to baseline following removal of the change-inducing stimulus.

high-volume short-duration stimuli. Motor evoked potentials are recorded distally as myogenic motor responses in the form of CMAPs from electrodes placed over key peripheral muscles of the upper and/or lower extremity. Common recording sites are the abductor pollicis brevis and long forearm flexors and extensors, and the adductor hallucis brevis and tibialis anterior, in the upper and lower limb, respectively. A decline in CMAP amplitude of greater than 75% compared to baseline reference values is indicative of potential motor tract injury (▶ Fig. 77.2).

77.10.3 Spontaneous EMGs

For spontaneous EMG recording, no stimulation is required. Fine-needle electrodes are placed in the muscles lying in the myotomal distribution of the spinal nerve root to be monitored. Intraoperative manipulations causing stretching, pulling, or compression of nerve roots produce neurotonic discharges and activation of the corresponding innervated muscles. These activated muscles then give rise to spike, burst, or train patterns on EMG recordings. Trains of higher frequency and amplitude represent significant nerve fiber recruitment and most likely indicate nerve injury following manipulation. Spikes and bursts, on the other hand, indicate proximity of an instrument to the nerve root in the operative field.

77.10.4 Stimulus-Evoked EMGs

Direct electrical stimulation of a pedicle screw with progressive increase in current strength is performed using a monopolar or bipolar probe. The normal cortical bone of an intact pedicle has high resistivity to the passage of electrical current. Any breach in the cortical continuity of the medial or inferior walls of the pedicle will cause current to flow through the path of least resistance resulting in depolarization of the adjacent exiting nerve root at that vertebral level. Needle electrodes placed in the distal muscles innervated by the nerve root will measure CMAPs at lower stimulus intensities in the breached pedicle than would be expected in an intact pedicle. A stimulus-induced myogenic response of less than 7 mA usually indicates higher probability of a pedicle wall breach (▶ Fig. 77.3, ▶ Fig. 77.4). However, variations in cut-off values exist due to differences in pedicle morphologies, for instance, between thoracic and lumbar levels.

77.11 Bailout, Rescue, and Salvage Procedures

Historically, the wake-up test has been used to indicate gross integrity of sensory and motor pathways. In this test, the depth

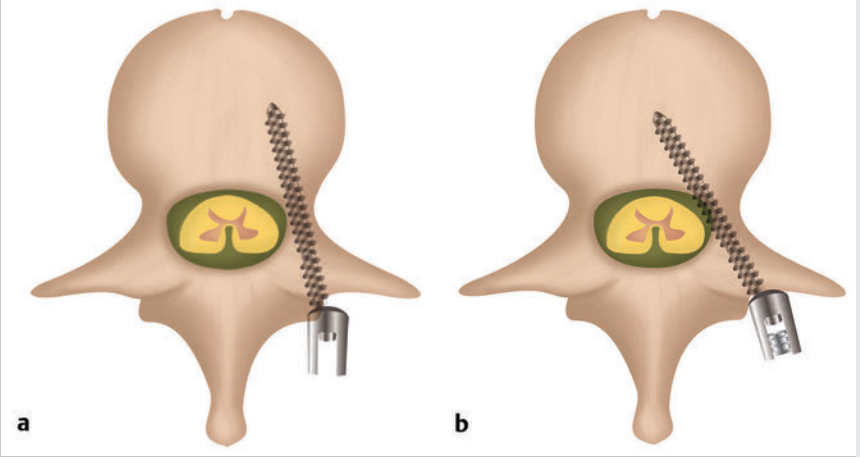

Fig. 77.3 Optimal screw placement within pedicle.

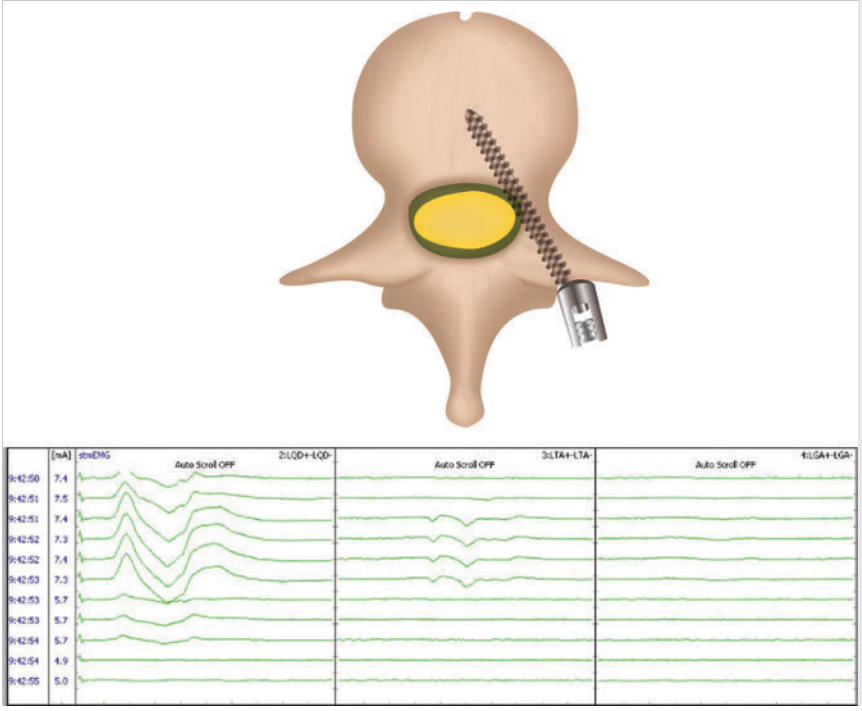

Fig. 77.4 Medial pedicle wall breach (top) causes triggered electromyograms to occur at a reduced threshold.

of anesthesia is reduced to the point that the patient can respond to commands and stimuli and make voluntary limb movements. In the context of modern neurophysiologic monitoring, this test can no longer be recommended as a standalone IONM modality. However, the wake-up test can supplement SSEP and MEP monitoring in situations where a likely neurologic event cannot be convincingly excluded. In such uncertain scenarios, a positive wake-up test can be of value to confirm that no gross neurologic injury has developed, despite abnormalities on SSEPs and MEPs.

Pitfalls

- Intraoperative neurophysiologic monitoring has been shown to have high sensitivity and specificity for detecting intraoperative neurologic injury, and its use is recommended for spinal deformity correction procedures. However, the level of evidence regarding whether this actually translates to reduced rates of neurologic deficits is relatively low. Thus, this technology should by no means be considered a substitute for sound surgical skills and judgment, as well as meticulous neural tissue handling during surgery.

Section XVI

Minimally Invasive Procedures

XVI

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78 Setup and Use of the Microscope in Spinal Applications

Thai Trinh, Jason Ferrel, and David Hannallah

78.1 Description

The surgical microscope has been utilized in the operating room (OR) for decades to provide superior magnification, stereoscope view, and illumination to the surgical field. Its first use in spine surgery dates back to 1977 when it was used to perform a microsurgical diskectomy in favor of the extensive laminectomy and intradural approach typical of the time. Since then, the surgical microscope has undergone numerous technological advancements that permit its use in a variety of surgical subspecialties including plastic surgery, neurosurgery, ophthalmology, and orthopaedics.

78.2 Key Principles

- Careful, intentional microscope preparation, positioning, and draping avoid complications and delays throughout the surgical procedure.
- Maintaining orientation of the microscope perpendicular to the patient prevents inadvertent dissection outside of the intended anatomical parameters.
- The spine surgeon should be familiar with the unique features of the microscope at his or her institution.
- Removing superficial tissues provides unobstructed visualization of the deep surgical field through the microscope.

78.3 Expectations

The microscope is composed of optical, illumination, and user-control systems. The optical system is composed of a multifocal objective lens, two binocular viewing tubes, as well as optional image and video-capturing devices for intraoperative documentation. The illumination system contains an illumination source (most commonly xenon) as well as controls to adjust the intensity and width of the beam. The user control system allows the surgeon to adjust magnification, zoom, and focus intraoperatively. The surgeon and surgical personnel should familiarize themselves with the terminology and location of these systems prior to operation of the surgical microscope (▶ Fig. 78.1).

Fig. 78.1 Components of the microscope include (A) a binocular viewing tube, (B) handlebars (C) with handset control, (D) and lens.

78.4 Indications

The surgical microscope is indicated for surgical procedures requiring improved surgical visualization and magnification.

78.5 Contraindications

Improperly functioning equipment (e.g., unable to maintain balance of microscope)

78.6 Special Considerations

- Planning of positional arrangements of equipment within the OR suite must be done in advance.
- Attention to the orientation and plane of the microscope maintains visualization of the intended zone of dissection.
- When a microscope is being used, special attention to maintaining a sterile operative field must be given as contamination can be frequent.
- Long instruments (i.e., long-tip Bovie electrocautery) are needed to work under the microscope without obstructing field of view.

78.7 Special Instructions, Positioning, and Anesthesia

In cases where utilization of the surgical microscope is anticipated, it is imperative that the OR be configured to optimize the surgical staff's ability to perform their duties without concern for contamination of the microscope or surgical field. This becomes increasingly important in cases utilizing a large fluoroscopic C-arm. The patient and the operating table should be positioned in the center of the room with any associated video equipment placed so that the scrub nurse and anesthesiologist are able to follow and contribute to the patient's care throughout the procedure.

The surgical microscope is usually placed directly behind the surgeon to facilitate handling during the procedure. If the arms of the microscope are not long enough to be placed behind the surgeon, it can be placed on the assistant's side. Careful attention must be paid to the position of the optical unit due to its asymmetric design to ensure the viewing tube with the shorter eye-ocular distance is always placed on the surgeon's side (▶ Fig. 78.2).

The surgical microscope should always be balanced in all six axes for precise positioning prior to the operation. To accomplish this, the swing arm should be placed perpendicular to the body of the control unit with the optical unit and pistol grips positioned with the eyepieces parallel to the floor. Although the exact mechanism in which the microscope is balanced varies by manufacturer and model, the majority of microscopes utilized today are capable of autobalancing with the push of a single button. Those microscopes without this capability require balancing each axis individually. In the event that the microscope

Fig. 78.2 An example of the microscope positioned across from the surgeon. Video equipment (if utilized) should be positioned so that the operative team can follow the case and assist the surgeon.

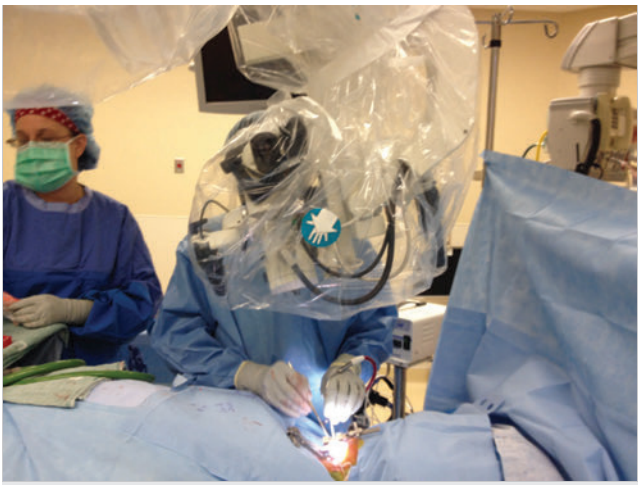

Fig. 78.3 Dissection should be carried out with the microscope positioned perpendicular to the operative field. This is especially important during dissection of the uncovertebral joints in the cervical spine.

needs to be repositioned intraoperatively, the surgeon should be familiar with the microscope's ability to rebalance without the need to reposition the swing arm and undrape the microscope.

Draping of the microscope is performed by the circulating nurse once the superficial dissection has been performed and anatomical landmarks (including appropriate vertebral level) have been confirmed by the surgeon. The drape, whose shape and configuration are manufacturer and model specific, is placed over the optical lens and securely fastened. The remaining portions of the drape are then positioned over the microscope and tightened around the joints to ensure that the sterility of the microscope is not compromised during the operation. It is important to remember that while the optical unit around the lens remains sterile, the lens itself may be uncovered depending on the drape manufacturer and is therefore unsterile.

78.8 Tips, Pearls, and Lessons Learned

- The swing arm and optical unit is positioned so that the objective lens is perpendicular to the patient and surgical field.
- It is critical to ensure that the microscope is looking straight down. Misdirection of the microscope towards the right or left of the patient could lead to inadvertent veering out of the intended surgical dissection. For example, during a standard Smith–Robinson approach for an anterior cervical diskectomy, misdirection of the microscope may lead to dissection lateral to the vertebral body and injury to the vertebral artery (▶ Fig. 78.3).
- Removing overhanging soft tissue improves visualization. Remaining soft tissue attached to the lumbar spinous processes or interspinous ligaments can impede the view of deeper anatomical structures.
- Adjusting the inclination and tilt of the optics unit to an ergonomic position prevents prolonged static cervical flexion and possible musculoskeletal fatigue and injury.

78.9 Difficulties Encountered

Contamination of the sterile operative field from the microscope can occur. Several studies have investigated the effect of the operative microscope on the incidence of postoperative infections following spine surgery. A recent study reported contamination rates of various portions of the microscope and covering drape ranging from 12 to 44%. Contamination was highest surrounding the shafts of the optic eyepieces on the main surgeon side (24%), "forehead" portion of both the main surgeon (24%) and assistant side (28%), as well as overhead portions (44%) of the drape. As a result, the authors recommended changing gloves after making adjustments to the optic eyepieces and avoiding handling any portion of the drape above the eyepieces as a means to reduce potential surgical field contamination (▶ Fig. 78.4).

Additionally, complications associated with positioning, focus, and lighting of the microscope can occur. Excessive tilt of the optics unit may lead to visual distortion of the plane of dissection and result in undesirable surgical dissections. Also, decreased working distances between the microscope and the surgical field while utilizing maximum light intensities may pose a significant burn risk to the patient.

78.10 Key Procedural Steps

- Preoperatively, microscope balancing should be completed, OR configuration planned, and sterile microscope drapes made available.
- Soft tissue obstructing view of the surgical field should be removed prior to introducing the microscope over the surgical field.
- The microscope should be positioned perpendicular to the patient and surgical field.
- The intensity and width of the beam should be adjusted based on the working distance to the surgical field.
- The lighting blind should be adjusted so that the width of the beam illuminates only the area of interest.

Fig. 78.4 Once the perforations protecting the viewing tubes have been removed, the surgeon should avoid touching this area unless gloves are changed.

- Intraoperative readjustments of the position of the optical unit are made by utilizing the handset controls located on the handlebars of most microscopes. These controls disengage the electromagnetic coupling within the optical unit to allow for free movement in all axes (**Video 78.1**).
- Following completion of the surgical procedure the microscope arms are bent inward and the microscope is transported for storage. The joints and foot breaks are then locked into position. Care and maintenance of the optical unit and lenses should be performed regularly according to the instructions provided by the manufacturer (see **Video 78.10**).

78.11 Bailouts, Rescue, and Salvage Procedures

- If the optical unit is observed to drift from the desired position, the surgeon should rebalance the microscope according to the manufacturer's instructions on intraoperative balancing.
- If the microscope cannot facilitate safe surgical intervention, surgical loupe magnification can provide improved visualization and magnification of the operative field as an alternative.

Pitfalls

- The surgical microscope presents the potential risk for contamination of the surgical field when prepped or used by those inexperienced in its operation. Ensure that all individuals taking part in the operative case are acquainted with the surgical microscope in advance.

79 Robotic Applications in Spinal Surgery

Mark E. Oppenlander, Christopher M. Maulucci, George M. Ghobrial, and Srinivas K. Prasad

79.1 Description

The use of robotics in spinal surgery promises to improve the accuracy, efficiency, consistency, and safety of minimally invasive procedures in a variety of applications. The greatest effort in spinal robotic development targets the placement of pedicle screws in the thoracic, lumbar, and sacral spine. Presently, the SpineAssist surgical robot (MAZOR Surgical Technologies Ltd.) and the da Vinci system (Intuitive Surgical, Inc.) have been used in spinal applications such as posterior pedicular fixation, anterior lumbar interbody fusion, and transoral odontoidectomy.

79.2 Key Principles

Three categories of surgical robots exist: (1) supervisory controlled systems where the robot performs the procedure autonomously with surgeon supervision, (2) telesurgical systems where the surgeon controls surgical instruments held by the robot using hand controls, and (3) shared-controlled systems where the robot and the surgeon control surgical instruments at the same time. The da Vinci system can be considered a telesurgical system. The majority of spinal robotic systems for pedicle screw insertion are shared-controlled systems, whereby a robotic arm aims a surgical instrument in a predetermined trajectory while the surgeon manipulates the instrument for pedicle screw placement.

79.3 Expectations

The use of a robotic interface has the potential to improve microsurgical dexterity by decreasing surgeon tremor. Robots do not fatigue and are able to perform tasks in repetition without loss of precision. The placement of pedicle screws with a robotic arm would conceivably increase accuracy and safety of screw placement while decreasing radiation exposure to the surgeon and the patient.

79.4 Indications

A robotic arm for the placement of pedicle screws could conceivably be used for a variety of indications, including degenerative spinal disease and deformity surgery. The da Vinci has been utilized for transoral craniocervical junction decompression, and may have utility in anterior thoracolumbar approaches (▶ Fig. 79.1).

79.5 Contraindications

Although indications are expanding for spinal robotics and contraindications have not been clearly delineated, the open approach remains the gold standard.

79.6 Special Considerations

The field of spinal robotics is still in its infancy and most surgeons will require a learning curve to effectively establish its use. Furthermore, room still exists for improvements in the robotic systems.

79.7 Special Instructions, Positioning, and Anesthesia

The use of a robotic arm for pedicle screw placement requires preoperative planning from a CT scan to establish the desired screw trajectories. The patient undergoes general endotracheal anesthesia and appropriate neuromuscular monitoring is established. For pedicle screw placement, the patient is positioned

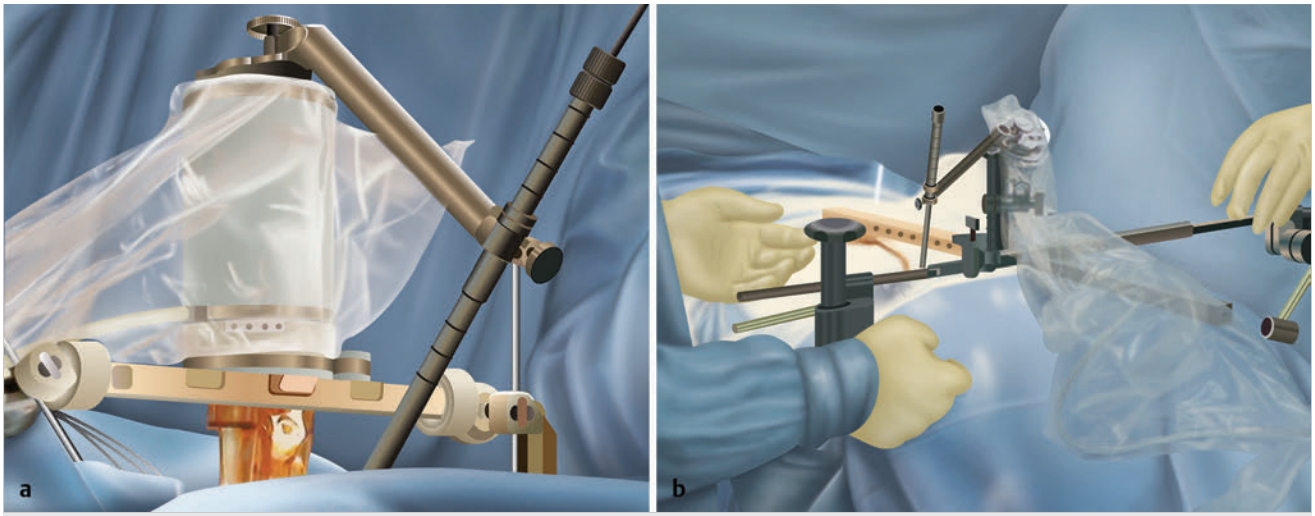

Fig. 79.1 The SpineAssist surgical robot (MAZOR Surgical Technologies Ltd.) **(a)** aids in spinal pedicle screw placement with predetermined trajectories via attachment of the robotic arm to the patient (**b**).

prone. SpineAssist has been used successfully with both open and percutaneous screw placement.

79.8 Tips, Pearls, and Lessons Learned

Early in the process of implementing the robotic arm for pedicle screw placement, intraoperative fluoroscopy may be useful to confirm screw trajectories. Also, different methods for attaching the pedicle screw robotic arm to the patient exist. Fixation of the robot arm to two or more bony connections via percutaneous K-wires may reduce the chance of inaccuracy.

79.9 Difficulties Encountered

The cannula that is inserted to the entrance point of the screw may be misguided for multiple reasons. In the case of degenerative facet joint hypertrophy, the cannula has potential to skid laterally. The cannula has sharp teeth at its tip to aid docking on the entry point to avoid potential skidding. In addition, the cannula may be deflected by muscle and fascia along its paramedian approach to the spine. Care should be taken to ensure that the cannula is not dislocated from the bony entry point during screw placement.

79.10 Key Procedural Steps

The SpineAssist robotic device is used to position surgical tools during spinal procedures. The procedural steps for its implementation are as follows:

- Obtain a computed tomography (CT) scan of the area of interest.
- Create a preoperative plan based on CT images: The surgeon plans an optimal entry point and trajectory for screw placement.
- In the operating room, place the arm by which the robot is anchored to the patient and verify system accuracy.
- The surgeon chooses which spinal level to place the screw, and the computer software aligns the robot accordingly into the correct screw trajectory.
- A cannulated drill guide is connected to the robot by the surgeon. The drill guide is now in the preplanned trajectory for screw placement.
- A stab incision is made and blunt dissection is carried out down to bone.
- The drill bit is inserted through the drill guide and used to drill through cortical bone in the set trajectory.
- A K-wire is inserted and a screw hole is now drilled over the K-wire.
- A screw of the appropriate size is placed over the K-wire.
- After instrumentation, decompression or fusion is performed where necessary.

79.11 Bailout, Rescue, and Salvage Procedures

Should the surgeon question the integrity of screw purchase or trajectory, intraoperative fluoroscopy may be used to confirm screw location. Ultimately, conversion to manual placement is the salvage procedure for robot-assisted surgery. Satisfactory position has been reported to be between 82% and 95% with the robot, improving as the user gains experience.

Pitfalls

- Surgeon inexperience: Because this is a new procedure, operative times may increase and confirmatory fluoroscopy may increase radiation exposure. Initial cases should be straightforward instrumentation procedures, reserving complex deformity cases for when sufficient experience has been gained.
- System deficiency: Spinal robotics is still under development; therefore, indications, efficacy, and accuracy are yet to be proven.

80 Endoscopic Percutaneous Lumbar Decompressive Techniques

Anthony T. Yeung

80.1 Description

Endoscopic transforaminal percutaneous lumbar decompressive surgery is a minimally invasive approach to the lumbar spine. Various endoscopes and surgical instruments exist to serve specific needs to probe, decompress, ablate, and irrigate painful pathoanatomy in the lumbar spine. For each approach, different decompression techniques may be employed such as the "inside-out," "outside-in," or "targeted" technique. Endoscopic decompression employs surgical visualization so that the surgeon can confirm that the preoperative pain generator has been adequately addressed.

80.2 Key Principles

A true minimally invasive approach to normal or painful lumbar pathoanatomy should provide access to the desired anatomy without damaging or affecting normal intervening tissues. The transforaminal approach allows for targeted foraminal, facet, nerve axilla, and pedicle access, including intradiskal therapies.

80.3 Expectations

The results of surgical intervention with the endoscopic approach should provide equivalent or superior results, but with less surgical morbidity and faster postoperative recovery when compared with traditional open translaminar approaches. In instances where decompression is incomplete, it does not prevent the surgeon from performing a later open surgical approach.

80.4 Indications

Indications for this approach are pathologies that are amenable to minimally invasive techniques diagnosed via physical examination, imaging studies, and diagnostic and therapeutic injections. A confirmatory response to diagnostic and therapeutic injections and ease of access to the pathoanatomy via an endoscope will help predict a favorable response to endoscopic decompression that utilizes the same trajectory as the presurgical injection. Diagnostic and therapeutic transforaminal injections, including diskography, utilize similar needle trajectories for the surgical approach.

80.5 Contraindications

Contraindications to this approach are dependent on the anatomical variations of normal and pathoanatomy in each individual patient. If the surgeon feels that access to pathology is constrained or limited as in the case of a migrated or extruded disk herniation relative to the size and location of the foramen, or access is mitigated due to coexisting degenerative conditions or when a wide decompression is necessary as in the setting of cauda equine syndrome, an alternative method of access may be desirable. The novice surgeon should begin with endoscopic decompression in patients who require only partial disk decompression to reduce intradiskal pressure, such as a small contained or protruded herniated disk in a patient with a tall disk height and a large neuroforamen. The surgeon should only consider treating more complex cases involving an extruded herniated nucleus pulposus (HNP), stenosis from narrowed neuroforamina, and facet hypertrophy after proficiency has been achieved. It takes great experience to have the skill to access and decompress the axilla of the nerve between the traversing and exiting nerve roots as this is often referred to as the "hidden zone."

80.6 Special Considerations

Having the proper endoscope and the accompanying surgical tools needed to perform the surgery safely and effectively is paramount. The scope should be able to fit inside a 6-mm inner-diameter cannula that is placed inside a degenerative disk. The walls of the cannula are intended to dilate a narrowed disk space enough for intradiskal visualization. The majority of degenerative disks can accept a 6-mm cannula if the disk space is adequately dilated by a blunt obturator. Access to the intradiskal pathoanatomy will allow the surgeon the ability to perform intradiskal therapy such as thermal annuloplasty, end plate preparation, or excision of disk fragments embedded within the anular fibers. A modular system gives the most flexibility, so instruments, cameras, and video towers from different vendors can be interchangeable. The endoscope configuration and irrigation channels consisting of at least one inflow and multiple outflow ports provides for the best visualization. Special tools, such as a Holmium: YAG (Ho: YAG) laser assists in ablating tissue or bone when indicated, and articulating or flexible instruments allow for ease of access depending on the anatomy. The multidirectional aspect of laser energy through various delivery probes provides surgical flexibility to access tight compartments and loosen embedded disk fragments within the anulus. Different vendors have surgical tools that are valuable adjuncts for surgical decompression not available from a single vendor. The surgeon, for these reasons, should have these tools available to use with a modular system.

Image guidance systems, although good for targeted spinal access, will not eliminate the risks of nerve and vascular injury due to anatomical variations in the foramen and soft tissue. If precautions are taken by the surgeon and proper protective shields are used, such as lead shields suspended from the ceiling, radiation exposure is minimized to reasonably safe levels when fluoroscopy is utilized. With experience, radiation exposure averages less than 60 seconds per foraminal decompression case.

80.7 Special Instructions, Positioning, and Anesthesia

Proper positioning of the patient facilitates the surgical approach and provides more consistent trajectories of needles and guide pins for the surgical placement of cannulas and instruments. Many surgeons prefer the prone position. Lateral positioning may be needed for morbidly obese patients (> 350 pounds) and if only a uniportal approach is required. The lateral approach allows for the abdomen to be free and not compressed as well as providing for airway access for the anesthesiologist.

The prone position is the most versatile and effective for several reasons. First, patients may be more comfortable in the prone position when sedated, and less likely to move around during surgery. Second, imaging in the posteroanterior and lateral plane may be more reliable and more familiar to the surgeon. A biportal approach is easily accomplished if needed for access to both the right and left foramen when the condition is bilateral. There are advantages and disadvantages of each position that help the surgeon target the pathoanatomy more consistently and safely.

The transforaminal approach is the most utilitarian approach for lumbar endoscopic surgery. It affords the surgeon the ability to visualize the neural elements by accessing Kambin's "safe zone" and the hidden zone in the nerve axilla formed by the traversing and exiting nerve roots. The translaminar approach, however, may be more useful at the L5/S1 level where the interlaminar window is larger, thus, facilitating easier retrieval of extruded disk herniations located in the paracentral and epidural space. Extruded disk herniations at L5–S1 may prove difficult through a transforaminal approach in patients with a high iliac crest or a hypertrophic facet joint. In this case, the translaminar approach may be favored.

80.7.1 Local versus General Anesthesia

The transforaminal endoscopic decompression procedure can be safely performed under monitored anesthesia care (MAC), where the patient is sedated and receives a combination of local anesthesia and short-acting intravenous drugs such as fentanyl or remifentanil and Versed (midazolam). It is important to develop an interactive working relationship with the anesthesiologist providing MAC to your patients by establishing protocols that provide adequate pain control and sedation during more painful parts of the procedure, while reducing sedation when patient cooperation is required. Verbal communication with a sedated patient in place of neuromonitoring is the most significant advantage of MAC. Some surgeons rarely use propofol in a very anxious patient and only during the introduction of the needle into the anulus. Once the needle is in the foramen, local anesthesia will provide more than adequate anesthesia to allow the cannula to fenestrate the anulus. The surgeon's ability to feel may also correlate with the patient's physical reaction. This provides haptic feedback experience to the surgeon. This is safer than a complete reliance on image guidance.

80.8 Tips, Pearls, and Lessons Learned

Experience and repetition will provide the best learning experience. Operating with an accomplished mentor surgeon is extremely helpful to shorten the learning curve. Transforaminal percutaneous decompression, even when safe access is obtained, requires adequate training to obtain the results of traditional surgery. Repetition will allow the surgeon to recognize pathoanatomy versus normal anatomy, such as furcal nerves versus foraminal ligaments. Simply being a good technician is not enough.

The most common and frequent technique breach is inadvertent advancement of the guidewire while inserting the dilator. Careful attention to advancement of the dilator with PA and lateral images and smooth advancement of the dilator over the guide pin will mitigate inadvertent advancement of the guide pin. It is advisable to pull or hold the guide pin back while the dilator is advanced into the disk to prevent inadvertent migration of the guide pin outside the disk cavity. A dilator with a side hole allows for needle anesthetization of the anulus and soft tissues in the path of the dilator. The strength and thickness of the dilator will actually make it safer to use the dilator manually to safely push a nerve out of the way.

80.9 Difficulties Encountered

Unexpected situations can occur, and the first caveat is to know when to abort the procedure and when to recognize potential hazards during the procedure. Taking steps to avoid complications requires knowledge gained from experience and from situations where an experienced surgeon demonstrates counter measures such as controlling irrigation pressure or controlling bleeding to mitigate the difficult situation encountered.

80.10 Key Procedural Steps

The first skill to learn is needle placement using fluoroscopy, aided by appropriate patient positioning on a radiolucent table (▶ Fig. 80.1). Coordinates are drawn on the skin to guide the needle in a posterolateral to medial border of the pedicle trajectory to reach the pathoanatomy inside the disk and in the epidural space. Determining the correct skin incision location and trajectory of the cannula and surgical instruments will make the procedure go smoothly and safely. A trajectory using the facet as the target ensures a safe and reproducible approach (▶ Fig. 80.2).

This procedure is carried out in an operating room, using local anesthesia. The conscious patient, attended by an anesthesiologist, is sedated with fentanyl and Versed. The patient communicates with the surgeon and is instructed to report any unusual painful sensations to the operating surgeon while the procedure is in progress. The approach begins by placing a needle freehand under biplanar fluoroscopic guidance to the dorsocaudal corner of the disk. Image guidance is discouraged because haptic feedback of needle pressure correlated with patient feedback reporting pain is important for the learning curve of needle placement. Foraminal and nerve anatomy

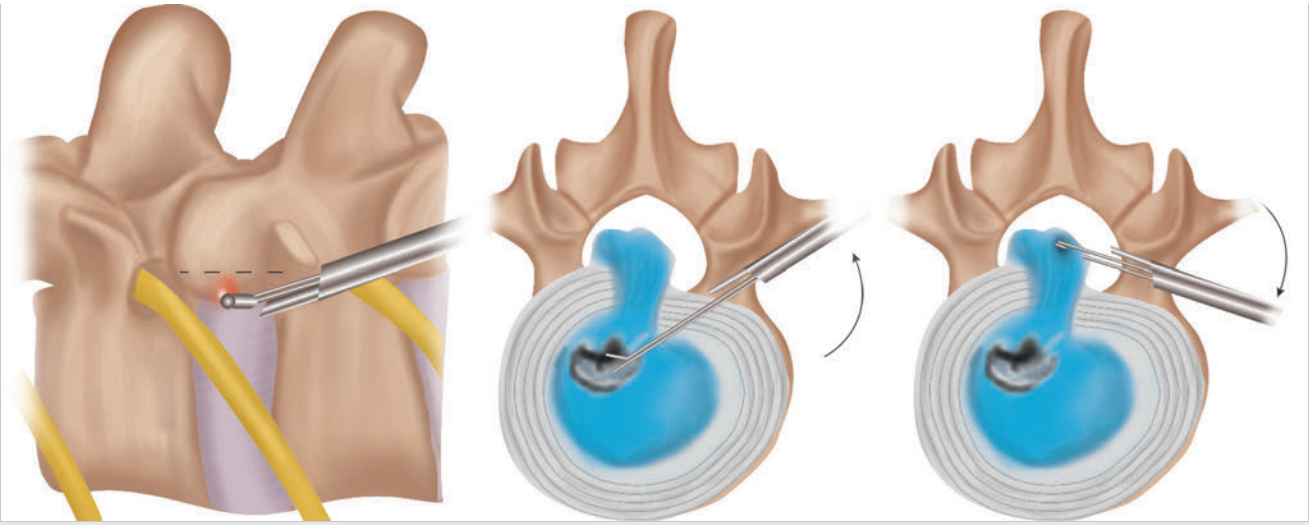

Fig. 80.1 The blunt obturator is used to guide the needle into the disk cavity by gently retracting the exiting nerve while sliding under the ventral facet. A cannula follows the obturator and the ventral facet is used as a fulcrum to direct the cannula trajectory for decompression.

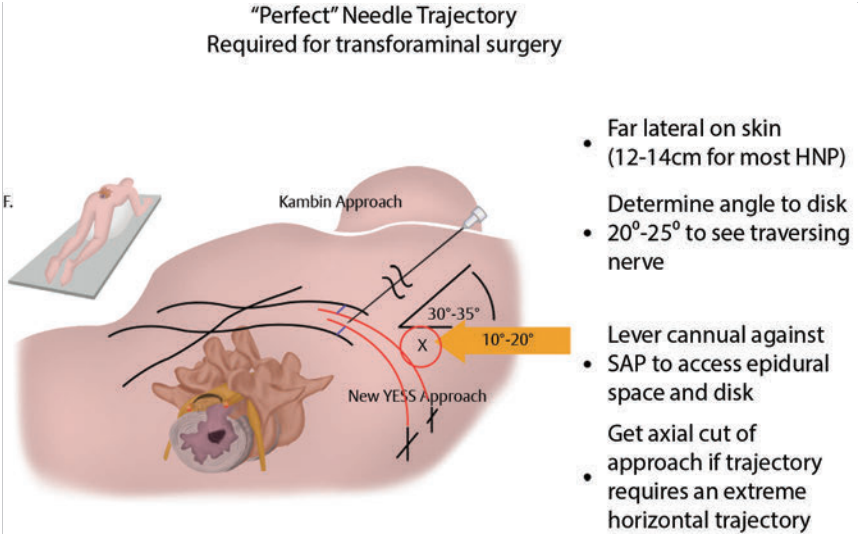
"Perfect" Needle Trajectory
Required for transforaminal surgery
Kambin Approach
30°-35°
10°-20°
X
New YESS Approach
• Far lateral on skin (12-14cm for most HNP)
• Determine angle to disk 20°-25° to see traversing nerve
• Lever cannual against SAP to access epidural space and disk
• Get axial cut of approach if trajectory requires an extreme horizontal trajectory

Fig. 80.2 The needle is passed with a 10- to 20-degree trajectory under the ventral facet as far dorsal and caudal as needed to avoid injuring the exiting nerve. The posteroanterior view on the C-arm shows the needle at the medial pedicular line or at least between the medial and mid-pedicular line. HNP, herniated nucleus pulposus; SAP, superior articular process; YESS, Yeung Endoscopic Spine System.

varies, and even a "perfect" needle placement in the foramen does not always allow safe passage of the needle because of the variations in foraminal anatomy (▶ Fig. 80.3). When the needle tip is close to the lateral facet or anular window, pain is often elicited. The conscious patient serves as a dependable alarm system to ensure that nerve irritation is not caused by needle injury to the nerve. The blunt obturator can be used to guide the blunt instrument past the nerve while the outside wall of the cannula will retract and protect the nerve. Neuromonitoring has not been shown to improve results or decrease surgical morbidity when local anesthesia is used. The usual painful disk pathology is located near the anulus, the facet capsule, and the posterior one-third of the disk space. Therefore, the operating tools are inserted from the skin window at a relatively horizontal trajectory of 15 to 25 degrees in the frontal plane toward the foraminal anular window. The needle is docked on the anulus as close to the medial pedicular line as possible, but not medial to that line. The cannula will then be just ventral to the facet. The facet is used as a fulcrum to lever the cannula and surgical instruments to the dorsal anulus and epidural space or ventral to the lateral disk space. To get the ideal trajectory, the patient's facet may require decompression of its ventral surface to get more dorsal in the foramen (▶ Fig. 80.4). The needle entry point is calculated from the PA and true lateral view of the lumbar spine and the skin window location is plotted. The combination of the skin window location and the foraminal anular window determines the needle trajectory.

80.10.1 Diskography

The diagnostic value of intraoperative provocative response is valuable for confirming the disk as the source of the pain. An evocative chromo-diskograph is a key clinical confirmatory test that links the suspected painful disk and the dye pattern to the patient's subjective pain complaints. Nonionic Isovue-300 (iopamidol) contrast is mixed with indigo carmine (indigotindisulfonate sodium) in a 10:1 ratio forming a blue dye. Blue staining of the degenerated nucleus pulposus and anular defects, using the vital dye indigo carmine in 10% concentration, visually identifies pathologic portions of the disk in contained or uncontained herniations. Contiguous disk fragments in the epidural space, disk tissue embedded in anular defects, and herniation tracts are also stained. In a nondegenerated disk, the X-ray contrast agent permeates the nucleus pulposus and forms a compact oval or bilobular nucleogram. There is no dye penetration into the substance of the normal impermeable anular collagen layers.

Therefore, the absence of an anulogram may represent a normal anulus. In degenerated conditions, clefts, crevices, tears, and migrated fragments of nucleus will be filled with contrast both inside the disk and along the herniation tract. This vital staining helps guide the surgeon for decompression and thermal modulation. The scope and associated tools are now used to surgically ablate the suspected pathologies.

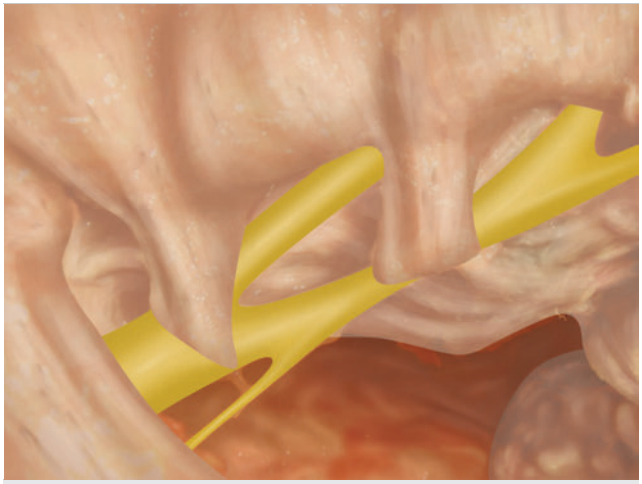

Fig. 80.3 Variations in normal foraminal anatomy requires surgeon awareness of optimal needle insertion trajectory to avoid nerve injury reaming outside the cannula may also be unsafe. Here at L3–L4 and L4–L5 Kambin's triangle is extremely small or almost nonexistent. The needle will have to be inserted at the most caudal and dorsal aspect of the foramen, sliding under and hugging the facet.

80.11 Bailout, Rescue, and Salvage Procedures

With percutaneous transforaminal decompression under local anesthesia, the procedure can be aborted at any stage of the procedure because no dissection requiring wound closure and suture is needed if the procedure is not proceeding as planned or anticipated.

One uncommon complication that is simply handled is a dural tear. If the tear is small, simply aborting the procedure will usually cause the dural tear to seal off from the operative site bleeding and the addition of a blood patch from the foramen may not be necessary. The patient may not even have a postoperative headache if the tear is small. If more decompression is needed, reoperation or approaching the disk from an alternative approach once the tear is healed can always be considered. With larger tears, a collagen patch through the cannula to the site of the tear using a DuraGen (Integra Life Sciences) patch or FloSeal (Baxter Healthcare) will compress and stop the

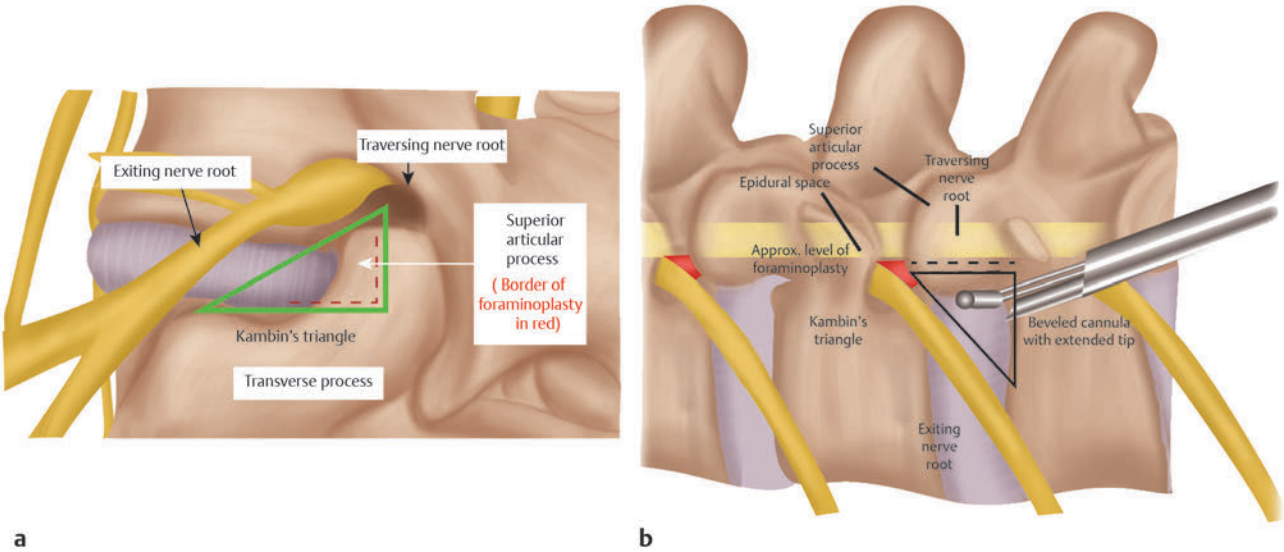

Fig. 80.4 **(a)** Foraminoplasty will allow instruments to access the epidural space to either allow exploration for extruded and sequestered herniated nucleus pulposus or for foraminoplasty for lateral stenosis, a common cause of failed back surgery syndrome. **(b)** Illustration of surgical foraminoplasty.

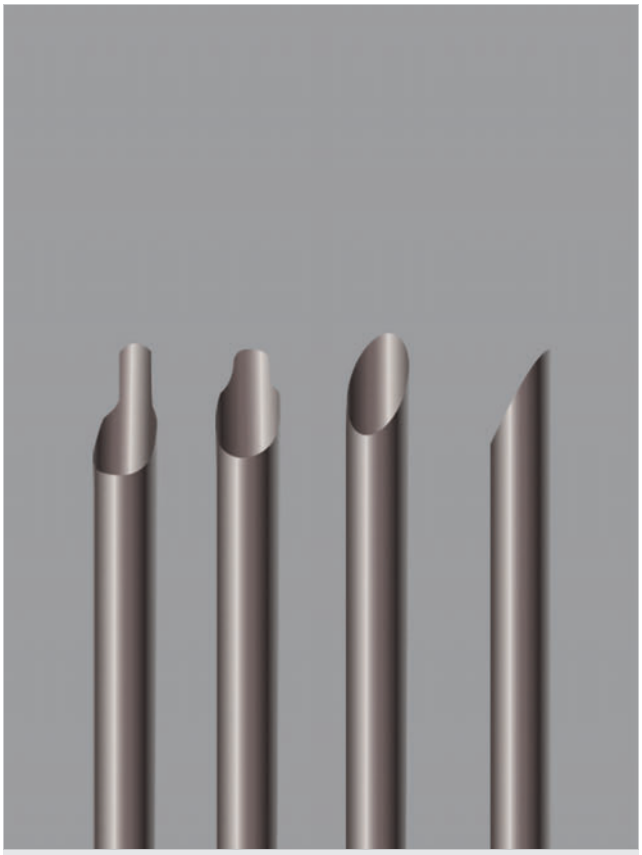

Fig. 80.5 Different cannula configurations for diskectomy and foraminoplasty are available to facilitate decompression. The window on the side of the cannula can be rotated to expose or to protect nerves or provide an opening for surgical tools. Four of the most frequently used cannula configurations are shown here.

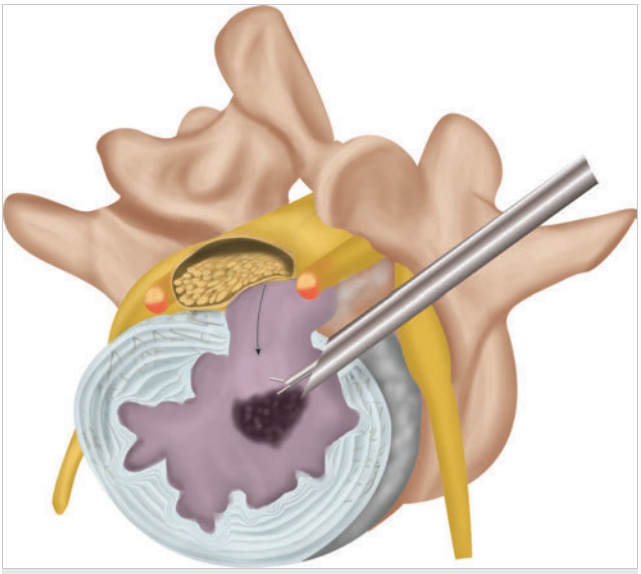

Fig. 80.6 The "inside-out" technique removes nucleus through a cannula to decompress the disk from the inside as well as outside, depending on the location and trajectory of the cannula, "targeting" the herniation and the pathoanatomy. Most herniations are safely removed by first decompressing the base of the herniated nucleus pulposus inside the disk, then levering the cannula and instruments dorsally against the facet to the epidural space. It may be necessary to perform foraminoplasty of the ventrolateral facet to gain access to the epidural space.

leak, and prevent extrusion of the rootlets of the cauda equina. If nerve rootlets from the cauda equina herniate from the tear, increasing the pressure and flow of irrigation fluid will push the rootlets back into the thecal sac. The location of the dural tear is usually on the ventral or foraminal surface of the thecal sac and difficult to repair; therefore, it is best to just tamponade the tear because there is no surgical cavity from surgical dissection.

Pitfalls

- The most common pitfall is the advancement of the guide pin outside the confines of the disk. This can occur during the advancement of the dilator when the guide pin is pushed forward. Care must be taken to smoothly advance the dilator with routine surveillance, checking the position of the guide pin with PA and lateral images during advancement of the dilator towards the anulus. As the obturator is being advanced, pulling back the guide pin while advancing the obturator and checking the guide pin position will prevent inadvertent advancement of the guide pin outside the confines of the disk space. Should the guidewire advance past the confines of the anulus, resist the temptation to pull the guide pin back and to simply resume the procedure. This may lead to introduction of bowel bacteria into an otherwise avascular disk space, and thus lead to a postoperative wound infection. The guide pin in this situation should be removed and discarded when any breach of the intradiskal cavity is suspected.
- The second most common pitfall is to continue operating when the patient feels pain despite seemingly adequate intraoperative sedation and analgesia. It is better to abort the procedure if the reason for pain is not expected or cannot be avoided. Safe decompression is always painless. Knowledge of variations of three-dimensional foraminal anatomy is imperative. The most significant structure in harm's way is the exiting nerve. Injury to this nerve can be avoided by learning how to navigate the needle to the facet capsule as dorsal and caudal as possible until the needle enters the foramen and docks on the anulus. A blunt dilator can then push the nerve out of the way with manual manipulation, followed by insertion of the operating cannula with its beveled end facing the nerve, then rotating the cannula to protect the nerve as it slips past the exiting nerve. Be extremely careful using reamers or surgical instruments outside the cannula without visualization. The surgeon must be able to use patient and manual pressure feedback when using a blunt dilator to first retract the nerve by pushing it out of the way, then using a beveled or tang extension (▶ Fig. 80.5) cannula with the open or beveled end sliding over the dilator facing the nerve. Once the cannula is past the nerve, it can be rotated, placing the nerve outside the cannula wall, protecting the nerve while decompression is performed inside the cannula. The patient may also feel radicular pain while the disk is being dilated with the obturator or cannula. A collapsed disk should not be overexpanded to restore "normal" disk height. When the patient has a significant collapsed disk, restoring disk space height can produce pain from the traversing nerves bilaterally during the dilation process. Excessive indirect decompression by increasing disk height may have adverse consequences.
- The surgeon should be able to see to operate. The exception is when surgery is performed intradiskally and with fluoroscopic control. Occasionally, bleeding from the anulus and epidural space obscures visualization. If this occurs, advance the cannula inside the disk and use the "inside-out technique" (▶ Fig. 80.6) to decompress the disk, then slowly pull the cannula back while controlling bleeding with a bipolar radiofrequency probe. If bleeding continues after visually guided decompression is complete, just let the blood flow out to the skin and the bleeding will eventually stop. The wound will stop bleeding from tissue swelling around the access portal. Occasionally, a catheter can be inserted into the wound with or without a Hemovac.
- When performing a foraminoplasty, especially in and around the dorsal root ganglion, postoperative dysesthesia, usually delayed, may occur 15 to 20% of the time. Provide a transforaminal epidural steroid block as soon as the dysesthesia is recognized and offer it to the patient. Combining the epidural block with a sympathetic block is very effective. Often the patient will decline the recommended block, indicating that the dysesthesia is not severe, and the patient only needs some reassurance that the dysesthesia will resolve. The alternative is to prescribe gabapentin or pregabalin. Usually one to three transforaminal epidural blocks will provide immediate relief. If there is skin sensitivity, add a sympathetic block to the transforaminal block. An approach is to use betamethasone 2 cc mixed with 2 to 3 cc .25% Marcaine for the transforaminal epidural block and 1 to 20 cc .5% Xylocaine plain for the sympathetic block. Patient reassurance is important.

81 Minimally Invasive Tubular Posterior Cervical Decompressive Techniques

Sina Pourtaheri, Alexander T. Brothers, Ki Hwang, and Arash Emami

81.1 Description

Posterior cervical decompression may be performed via an open or minimally invasive approach. Minimally invasive tubular cervical decompression may have benefit over conventional cervical laminectomies and/or foraminotomies via better preservation of the soft tissue sleeve and avoidance of increased soft tissue dissection-related complications.

81.2 Key Principles

Minimally invasive tubular cervical decompression is primarily used for cervical foraminotomy, laminotomy, and/or diskectomies, and is often not employed for laminectomy. Cervical laminectomies without fusions can be associated with postlaminectomy kyphosis. Relief of nerve root-related symptoms is the primary objective of the surgery. Minimally invasive cervical foraminotomies/laminotomies decompress pathologies related to spondylotic changes impinging the affected nerve root, such as disk herniations, and facet and capsuloligamentous hypertrophy.

81.3 Expectations

Thorough unilateral foraminotomy and/or diskectomy relieving cervical nerve root impingement is the major goal of the surgery. Improvement in cervical radiculopathy is expected with mild, approach-related postoperative pain. No particular postoperative activity restriction and/or brace is required.

81.4 Indications

- Disk herniation (paramedian, foraminal, extraforaminal)
- Focal stenosis from ligamentum hypertrophy
- Lateral recess stenosis with radicular symptoms (hemilaminotomy)
- Radiculopathy and foraminal stenosis (foraminotomy)
- Patients that are at higher surgical risk for more invasive surgery

81.5 Contraindications

- A disk herniation located primarily in the midline making a posterior diskectomy dangerous neurologically
- Relative contraindications
  - Cervical kyphosis
  - Cervical instability

81.6 Special Considerations

Partial facetectomy is often required for adequate nerve root decompression and visualization. It is recommended to remove less than 50% of the facet complex; however, biomechanical studies have shown that removal of even 25% of the facet decreases cervical stability both rotationally and translationally. Remove just enough of the facet joint for adequate nerve root decompression and visualization (▶ Fig. 81.1). Preserve as much of the posterior and posterolateral ligamentous complex as possible.

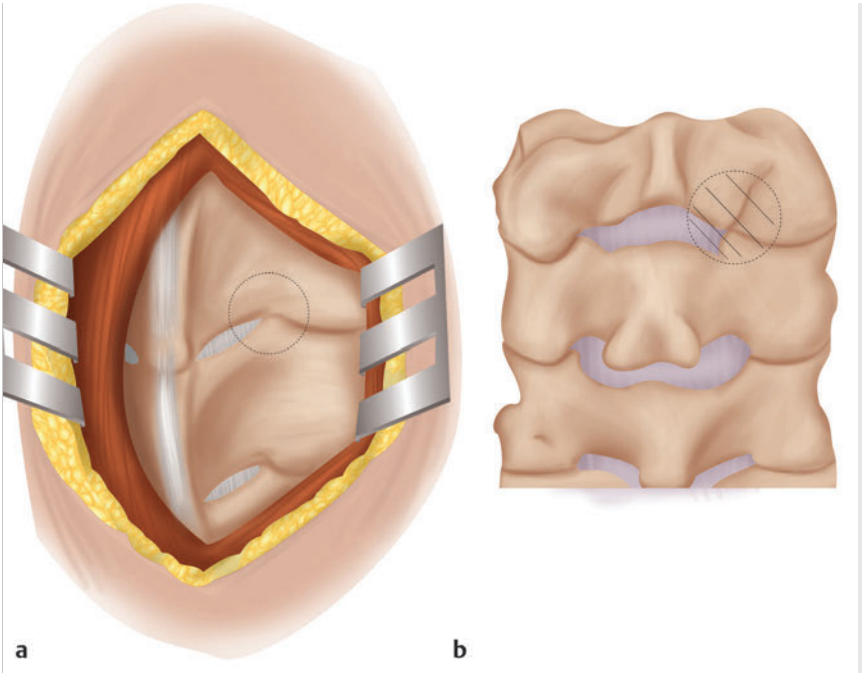

Fig. 81.1 Posterior cervical landmarks of a tubular decompression. **(a)** Identify the lamina–facet junction and other bony landmarks for cervical foraminotomy. (**b**) Resect the inferior edge of the superior lamina, the superior edge of the inferior lamina, and the medial aspect of the facet complex as needed.

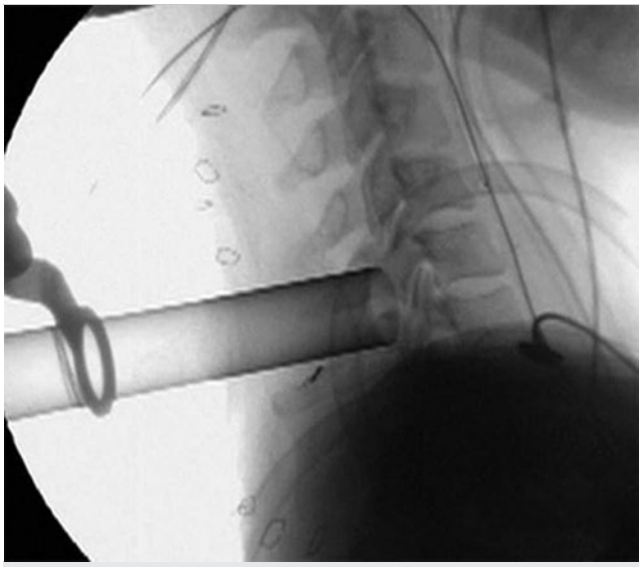

Fig. 81.2 Tubular trajectory under lateral fluoroscopy. The tube is placed at the level of the facet joint and parallel to the disk space.

81.7 Special Instructions, Positioning, and Anesthesia

General anesthesia is performed in a prone or sitting position. We prefer to position the patient prone on a Wilson frame and Mayfield holder with three pins.

81.8 Tips, Pearls, and Lessons Learned

- Patient selection and appropriate workup including magnetic resonance imaging (MRI) demonstration of nerve root impingement
- Identifying the exact compressive pathology for the patient's symptoms and its relative location to the affected nerve root allows for a focused operative plan.
- On fluoroscopy, confirm that the tube is at the level of the facet requiring a decompression, while parallel to the disk space. This avoids unnecessary soft tissue dissection (▶ Fig. 81.2). An improper trajectory is a common problem in the initial surgical learning curve, which prolongs surgical times.

81.9 Difficulties Encountered

Developing the correct trajectory of the tube in the sagittal plane is a challenging task. Soft tissue creep is common with smaller tubes. Durotomies are possible, but infrequent. Copious epidural venous plexus bleeding can affect visualization and methodical hemostasis is prudent.

81.10 Key Procedural Steps

- Perform a vertical incision that's approximately 1 cm long and 1 cm lateral to the midline.
- A longitudinal incision of the paraspinal muscle fascia is performed prior to dilator placement.
- Place the initial dilator and confirm trajectory on lateral fluoroscopy.
- Sequentially dilate over the initial tube with firm downward pressure to prevent soft tissue creep, and lock the final tube into the locking arm.
- A final lateral fluoroscopic image is used to confirm the correct trajectory. It is common for the tube to move during the dilation process; this confirmatory view is crucial.
- Some of the soft tissue that creeps into the operative field is excised to identify the junction of the lamina and facet, as well as the edges of the superior and inferior lamina.
- The undersurface of the lamina is freed from the ligamentum flavum with an angled curette. With a bur, thin out the inferior edge of the superior lamina and the superior edge of the inferior lamina to the level of the pedicle.
- With a Kerrison rongeur, remove the thinned-out edges of the lamina.
- The ligamentum flavum is removed and the nerve root is identified and freed with a nerve hook.
- The medial facet may be burred to better visualize the nerve root, and to obtain a better decompression.
- Palpate with a probe the pedicle above and below. A thorough foraminotomy carries out the decompression from pedicle to pedicle.
- For a diskectomy, preoperative MRI should be used to identify the location of the disk herniation in relationship to the nerve root. Usually, it is caudal to the nerve root.
- The posterior longitudinal ligament is incised and the diskectomy is performed with micropituitary forceps.
- Palpate thoroughly below and in front of the nerve root to ensure the herniated fragment is completely removed.
- Proper hemostasis is achieved and an injectable suspension of methylprednisolone can be adjunctively placed over the nerve root.

81.11 Bailout, Rescue, and Salvage Procedures

- If adequate exposure and visualization cannot be obtained, redirect the tube and confirm its trajectory under lateral fluoroscopy. The usual culprit for limited exposure is improper trajectory.
- If redirection does not allow the proper exposure, another option is to use a large diameter tube or convert to a mini-open approach.
- Often, a diskectomy is difficult to preform without excessive retraction of the nerve root. If unroofing the nerve root is not enough to alleviate the symptoms, then an anterior cervical diskectomy and fusion may be indicated as a salvage procedure.

Pitfalls

- An inadequate diskectomy is a common mistake and a thorough review of preoperative MRI is crucial to pinpoint the exact location of the herniated disk. Furthermore, many disk herniations cannot be relieved via a posterior foraminotomy. A careful review of the preoperative MRI may show that an anterior cervical diskectomy and fusion is a better treatment option.
- Overresection of the facet joint can lead to instability, facet arthropathy, and subsequent cervical spondylosis and complications. By clearly identifying the junction of the lamina and facet, one can adequately assess how much of the medial facet is being removed.

82 Mini-Open Anterolateral Retropleural Approach for Thoracic Corpectomy

Amir Ahmadian, Ali A. Baaj, and Juan S. Uribe

82.1 Description

Anterior column support is crucial for adequate spinal stability. Vertebral body (VB) support and anterior column restoration can be challenging, especially in the thoracic spine. Traditional anterior open approaches require an access thoracic surgeon, deflation of lung, and frequently mobilization of great vessels within the thoracic cavity. Mini-open posterolateral retropleural approach minimizes approach-related morbidity. Corpectomy is used to address a variety of spinal pathologies to include osteomyelitis, traumatic fractures, deformity, and tumor invasion that leads to structural instability.

82.2 Key Principles

Mastery of regional anatomy specific to thoracic level of interest, adequate exposure, and preservation/decompression of neural elements are critical to successful surgery. Patient positioning, surgical orientation, and appropriate utilization of intraoperative fluoroscopic images are also important principles.

82.3 Expectations

Complete vertebral corpectomy and adequate ventral spinal cord decompression can be accomplished. Large footprint expandable cage and plate can be placed to provide restoration of the anterior vertebral column.

82.4 Indications

- Thoracic burst fracture:
  - With instability
  - With neural element compression
- Vertebral body tumor
- Vertebra plana
- Osteomyelitis
- Deformity

82.5 Contraindications

- Compression arising from posterior spinal elements only
- Previous ipsilateral chest wall or lung parenchymal surgery (relative)

82.6 Special Considerations

Appropriate preoperative planning and imaging (computed tomography/magnetic resonance imaging) should be performed to determine side of approach, extent of needed decompression and regional anatomy. Consideration for preoperative angiography/embolization should be given to vascular tumors. Special attention should be given to location and attachments of the diaphragm and position of great vessels.

82.7 Special Instructions, Positioning, and Anesthesia

The patient is placed under general anesthesia and is positioned in a lateral decubitus position with adequately padded arms and legs (▶ Fig. 82.1a, b). Intraoperative neural monitoring (somatosensory/motor evoked potentials) is used when neural element compression is present. Double-lumen endotracheal tube is not required with retropleural approaches. Fluoroscopy is used to localize thoracic level of interest and used to ensure the patient is in direct lateral prior to being taped in place.

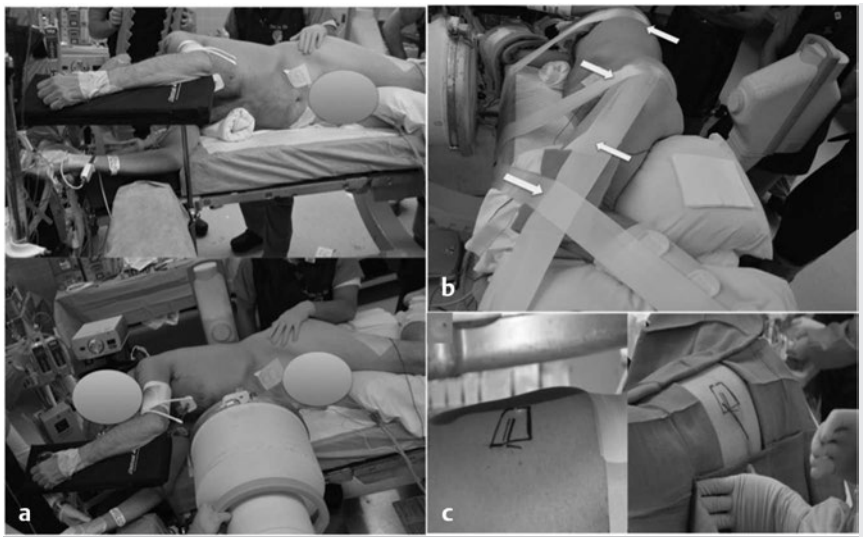

Fig. 82.1 Positioning. (**a**) The patient is in a lateral decubitus position with axillary role/padding. (**b**) The position is maintained with silk tape and fluoroscopy is used to ensure the patient is in neutral position. (**c**) The vertebral body is mapped out on the skin and intervening rib is marked for incision.

82.8 Tips, Pearls, and Lessons Learned

Level-specific considerations of the thoracic spine when utilizing the mini-open retropleural approach include:

- Inability to access high thoracic lesion (T1–T4) due to the position of the scapula
- Release of diaphragmatic attachments to rib/transverse process and VB (T10–L1)
- Transitional anatomy from retropleural to retroperitoneal (T11–L1)

Localization of thoracic level can be done from a bottom-up approach by locating the T12 rib or sacrum. A spinal needle can be placed at the spinous process/lamina of the level of interest to maintain localization when moving from anteroposterior to lateral fluoroscopy. Rib corresponding to level should be correctly identified for incision and approach corridor.

The plane of dissection is between the parietal pleura and endothoracic fascia on the anterior surface of the rib. This plane can be preserved and expended to gain access to the VB with careful blunt dissection.

82.9 Difficulties Encountered

82.9.1 Identification/Preservation of Parietal Pleura

Once a portion of the rib is removed, the ventral surface of the rib and endothoracic fascia is separated from the parietal pleura with combination of finger/Kitner blunt dissection. This dissection should be wider than the surgical corridor (i.e., extended to ribs above and below) to allow parietal pleura to fall away from chest wall. Translucency of the parietal pleura helps with its identification.

82.9.2 Identifying Posterior Extent of Vertebral Body

Retropleural dissection is carried out to the articulating rib head and VB. The rib head must be removed to access the pedicle, neural foramen, and ventral dura. With the rib head removed, the foramen is carefully palpated to identify the pedicle and posterior extent of body.

82.9.3 Diaphragm

The diaphragm has attachments to the ventral surface of T10–T12 ribs and transverse processes down to L1–L2. These attachments hinder blunt dissection at these levels and need to be sharply dissected as the VB is approached.

82.10 Key Procedural Steps (Video 82.1)

82.10.1 Incision (▶ Fig. 82.1c)

The VB is mapped out on the skin and the corresponding rib is chosen. A 6-cm incision is made on the corresponding rib preserving the neurovascular bundle on the inferior portion of the rib.

82.10.2 Parietal Pleura Identification and Dissection

The soft tissue and neurovascular tissue is carefully separated from the rib. If necessary, 4 to 6 cm of rib can be cut and used later for autograft. The parietal pleura (transparent) are identified deep to the endothoracic fascia. Meticulous finger and Kitner blunt dissection is carried out to the corresponding body. This dissection is also extended cephalocaudal to allow the pleura to fall away.

82.10.3 Pedicle/Foramen/Rib Head (▶ Fig. 82.2)

Once the VB is exposed, the articulating rib head is identified and removed to expose the foramen and pedicle.

82.10.4 Diskectomy/Corpectomy/Cage Placement (▶ Fig. 82.3)

Diskectomy is performed above or below the VB of interest. Next, an osteotome is used to remove a large portion of the VB.

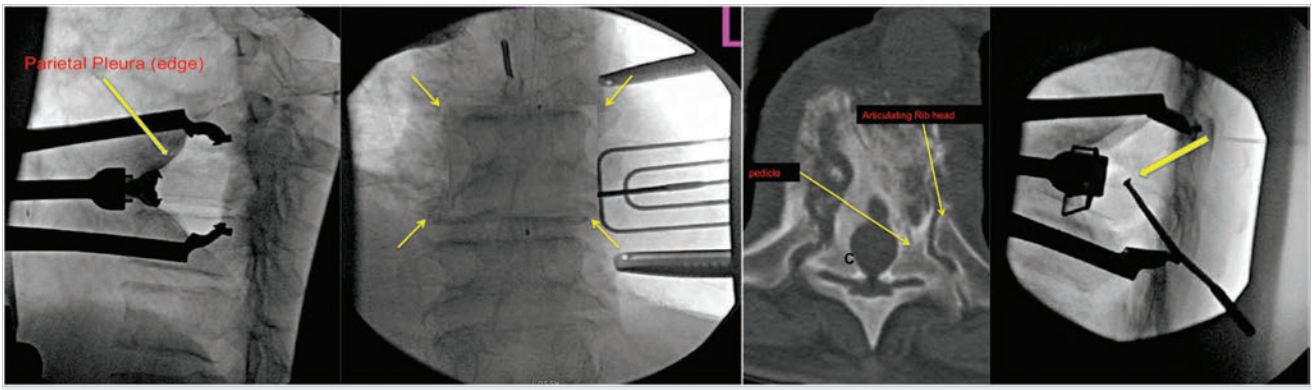

Fig. 82.2 Fluoroscopic approach: Lateral and anteroposterior fluoroscopy showing vertebral body prior to corpectomy. Axial computed tomography shows the relationship of rib head to the pedicle/foramen.

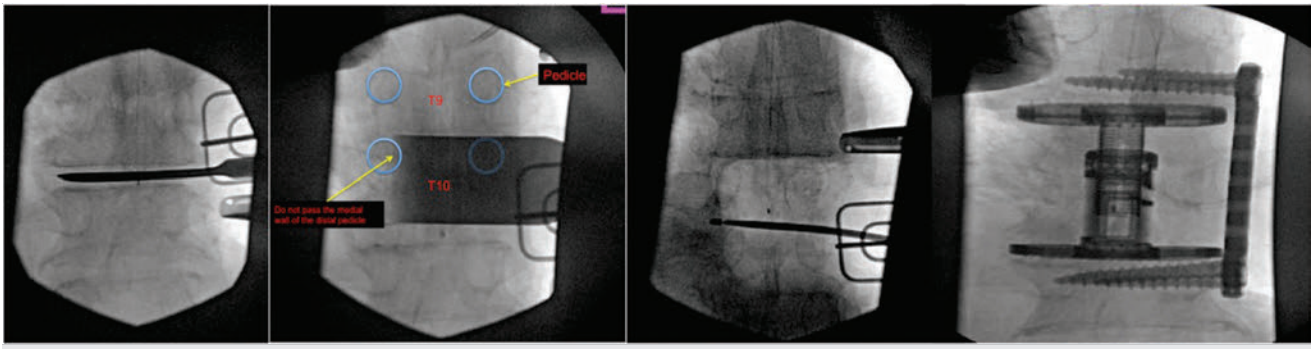

Fig. 82.3 Diskectomy and corpectomy: Fluoroscopic imaging of diskectomy above and below the vertebral body of interest, followed by osteotome and drilling of the vertebral body. Cage and lateral plate construct are also shown.

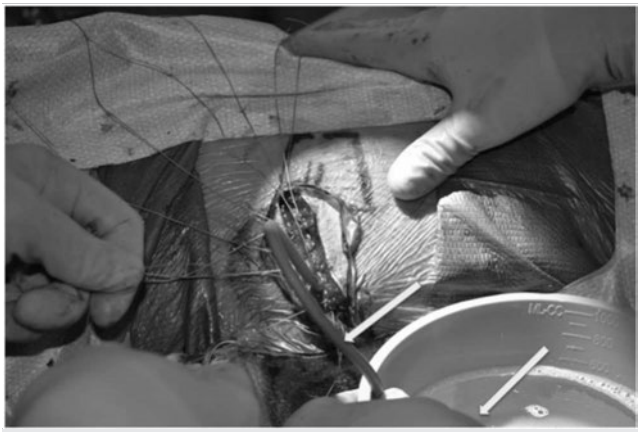

Fig. 82.4 Closure: The use of a red-rubber catheter leading into a water basin with concomitant Valsalva to express excess air from thoracic cavity is depicted.

Fluoroscopy is used to ensure that the osteotome does not pass the medial wall of the distal pedicle so as to prevent injury to contralateral structures. A high-speed drill is then used to remove the remaining VB. Meticulous dissection with drill and curettes is undertaken posteriorly to expose the ventral dura.

Remaining end plates above and below are prepared and an expandable cage is placed.

82.10.5 Closure (▶ Fig. 82.4)

If the parietal or visceral pleura are not violated, then a chest tube is not necessary. A Hemovac drain is then placed in the retropleural space. The intercostal muscle is approximated and in cases where the pleural space is violated, a red-rubber catheter is temporarily placed in the retropleural space. The catheter is placed underwater in a basin and anesthesia assists with Valsalva to remove remaining air from the retropleural space. At maximum Valsalva, the red-rubber catheter is removed and simultaneously the last facial suture closed. A Hemovac drain can be placed within the retropleural space to evacuate postoperative surgical bed oozing.

Instrumentation can be placed using anterior/lateral plating or open/percutaneous pedicle screw placement.

82.11 Bailout, Rescue, and Salvage Procedures

In cases where a retropleural plane cannot be developed, the procedure should not be aborted but rather continued in a transpleural fashion. Great care should be taken not to violate the visceral pleura. Posterior transpedicular and costotransversectomies are still viable bailout/salvage options and can be considered as an adjunct to the anterolateral approach with pathologies that extend to the posterior vertebral elements.

Pitfalls

- Visceral pleura injury (pneumothorax): A postoperative chest tube is required to prevent tension pneumothorax.
- Cerebrospinal fluid (CSF) leak: Direct repair is difficult; a postoperative lumbar drain is recommended to minimize retropleural/thoracic pseudomeningocele.
- Neurovascular bundle injury: This is located on the inferior aspect of the rib and susceptible to injury during partial rib resection. Injury may be a cause of postoperative or delayed sensory disturbance (dysesthesia/analgesia).
- Vascular injury: This is located in the anterior aspect of the VB; injury can occur during anterior extension of VB exposure or with aggressive corpectomy.
- Spinal cord injury: Especially vulnerable with a compressive lesion such as a calcified or large thoracic disk herniation

83 Minimally Invasive Tubular Posterior Lumbar Decompressive Techniques

Amir Ahmadian, Armen Deukmedjian, and Juan S. Uribe

83.1 Description

The removal of bone and soft tissue that is compressing the central canal and/or foramina in the lumbar spine using a minimally invasive tubular approach in an effort to minimize the approach-related footprint needed for adequate decompression.

83.2 Key Principles

Minimally invasive posterior lumbar decompression includes laminectomy, hemilaminotomy, as well as unilateral or bilateral foraminotomy can be performed using a tubular approach. The approach can be used to address stenosis caused by degenerative spondylosis, ligamentous hypertrophy, or herniated disk. Mastery of regional anatomy and appropriate utilization of intraoperative fluoroscopy are important principles for successful decompression with a tubular approach.

83.3 Expectations

Adequate laminectomy and bilateral foraminotomy can be performed from unilateral tubular approach in patients with symptomatic stenosis who do not otherwise require fusion. Immediate or early postoperative symptomatic relief can be expected with root decompression and herniated disk removal. Mild-to-moderate postoperative pain can be easily controlled. No specific postoperative activity restriction is required.

83.4 Indications

- Disk herniation (medial, paramedian, foraminal, extraforaminal)
- Focal stenosis from ligamentum hypertrophy
- Neurogenic claudication (laminectomy)
- Lateral recess stenosis with radicular symptoms (hemilaminotomy)
- Radiculopathy and foraminal stenosis (foraminotomy)
- Patients that are at higher surgical risk

83.5 Contraindications

- No absolute contraindication to tubular decompression
- Relative contraindications include pathologies that require internal fixation/fusion:
  - Anterolisthesis causing central canal stenosis
  - Instability with movement of dynamic imaging
  - Osseous fracture
  - Deformity correction

83.6 Special Considerations

Tubular lumbar decompression, like open decompression must be tailored to patient-specific needs and pathology. Facetectomy should be limited to 50% of the facet complex to prevent segmental instability. When possible, an attempt must be made to preserve the posterior tension band provided by the interspinous ligament. Preoperative planning and imaging (magnetic resonance imaging/computed tomography) is required to define the side and angle of the tubular approach.

83.7 Special Instructions, Positioning, and Anesthesia

For a minimally invasive tubular approach to the lumbar spine, the patient should be under general anesthesia and placed in a prone position on a Wilson frame (Mizuho Medical Products) or chest roles. The Wilson frame is preferred because it decreases lumbar lordosis and increases interlaminar space. The patient should be placed in a slight reverse Trendelenburg position with eyes protected. Arms are placed near the head and fluoroscopic images are used to tailor incision and placement of tubular retractor.

83.8 Tips, Pearls, and Lessons Learned

Patient selection and strict direct imaging correlation to clinical symptoms is imperative to selective minimally invasive tubular techniques. Axial back pain is a poor indicator to selective decompression as compared with radicular symptoms.

- Determine the specific contributors (herniated disk, ligamentum flavum hypertrophy, facet hypertrophy, congenital narrow canal, synovial cyst, etc.) to neural element compression prior to surgery.
- Determine true midline (spinous process) with fluoroscopy. Use spinal needle to confirm adequate placement of trajectory of tubular system with anteroposterior (AP) and lateral fluoroscopy prior to incision (▶ Fig. 83.1, ▶ Fig. 83.2).

- Ligamentum flavum can be used as a natural barrier to the dura and is especially helpful when attempting contralateral foraminal decompression from a unilateral approach.
- Extent of bony decompression should be to preserve the pars interarticularis to prevent causing unintentional instability.

83.9 Difficulties Encountered

Soft tissue encroachment can occur under the retractor with inadequately sized tube. Soft tissue fibers can be brushed out of

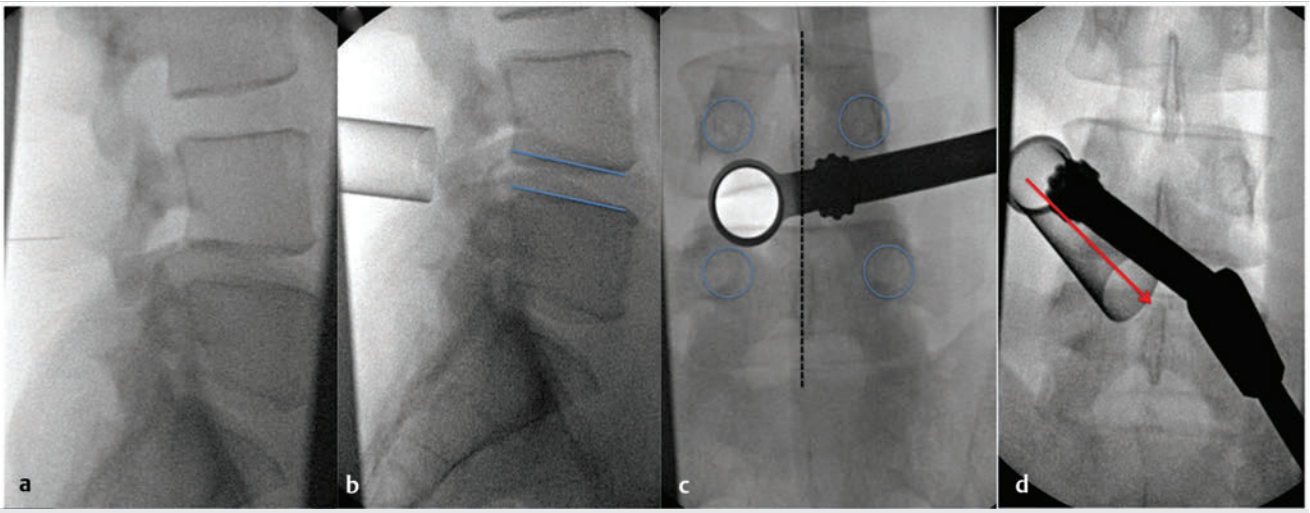

Fig. 83.1 Posterior lumbar tubular decompression. (**a**) Fluoroscopic guidance to level of interest. Spinal need is used to determine level and trajectory. (**b**) Tubular retractor placement (lateral view) in line with intervertebral disk space for microdiskectomy. **(c)** Tubular retractor placement (anterior-posterior view) just medial to the pedicle for microdiskectomy. **(d)** Tubular retractor placement (anteroposterior view) exhibiting medial angulation for laminectomy/hemilaminectomy and contralateral decompression.

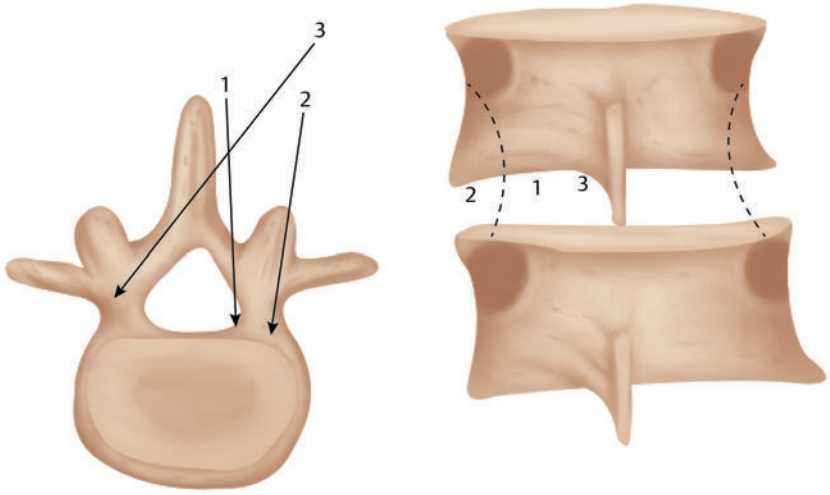

Fig. 83.2 Sketch of tubular trajectory for decompression: 1. Median/paramedian trajectory for foraminotomy, hemilaminectomy, and microdiskectomy. 2. Far lateral trajectory for lateral foraminal diskectomy (edge of pars interarticularis). 3. Medial trajectory for laminectomy and contralateral lateral recess and foraminal decompression.

the field or bluntly dissected. Determining trajectory of approach (midline, translaminar, interlaminar, or extraforaminal) and appropriate levels may be challenging without preoperative planning.

Cerebrospinal fluid (CSF) leak can occur from dural tear, which can be prevented by meticulous surgical technique. Direct repair of dural tear is challenging with tubular approach. A muscle/fat patch may be a viable option in this setting to treat an active CSF leak.

Epidural venous bleeding is routinely encountered and in most cases easily controlled. Meticulous hemostasis is imperative to prevent postoperative epidural hematoma.

83.10 Key Procedural Steps

- Vertical incision is made equivalent to the tubular diameter that is to be used.
- Incision is made 1 to 2 cm lateral to the midline.
- Sharp separation of the muscle fascia prior to dilator placement is needed.
- Sequential dilators are used to bluntly separate muscle fibers.
- Consistent downward pressure on dilators and tube ensure minimal muscle encroachment into the surgical field.
- Special care is needed not to dock tubular system too lateral on the facet complex.
- Inferior and superior limits of the designated lamina should be identified.
- Laminectomy can be performed from the inferior edge of the lamina with a high-speed drill in the cephalad direction.
- Ligamentum flavum should be identified and bluntly separated (Penfield no. 4, nerve hook) and carefully removed (Kerrison rongeur) to visualize the dural sac and associated epidural adipose tissue.
- Extraforaminal trajectory requires identification of the lateral boarder of the pars interarticularis. Blunt dissection from the caudal to cephalad direction so as not to injure the exiting nerve root.

83.11 Bailout, Rescue, and Salvage Procedures

The minimally invasive tubular approach has the disadvantage of limited surgical field/view, transition to a traditional open approach is an option if the exposure is inadequate to address the pathology or repair the injured dura. Direct repair of a CSF leak can be attempted or onlay patch used.

Reoperations should be done in a mini-open or open approach. Scarring from previous surgery can alter regional anatomy making tubular approaches more challenging.

Pitfalls

- Overzealous diskectomy can lead to injury to the retroperitoneal vessels. The anterior longitudinal ligament provides a natural barrier though it is present at the midvertebral body, making vessels just lateral to the anterior longitudinal ligament, such as the iliac veins, more vulnerable.
- Leaving a partial compressive lesion behind is a potential pitfall requiring reoperation. Imaging should be reviewed for migrated disk fragments and contralateral lateral recess stenosis in the setting of ligamentum flavum hypertrophy. Meticulous undermining of the posterior longitudinal ligament should be done with microinstruments to ensure all fragments are removed.

84 Presacral Interbody Fusion

David Hart, Sean Reynolds, and Teresa Schroeder

84.1 Description

Axial lumbar interbody fusion (AxiaLIF) is a minimally invasive lumbosacral fusion technique that employs an axial approach to the spine, utilizing a corridor that minimizes neural and vascular risks, while preserving bony and soft tissue supporting structures to achieve fusion at the L5–S1 level. Instrumentation is inserted through a 2- to 3-cm incision near the coccyx to create and preserve a safe working channel along the presacral space to the L5–S1 intervertebral disk space. The disk space is prepared to facilitate fusion and graft material is added; a threaded titanium rod is then inserted to fixate the L5–S1 motion segment. This safe and reproducible transsacral axial access to the L5–S1 intervertebral disk space maintains the integrity of the anulus and obviates the need to dissect, mobilize, and retract the anterior and posterior soft tissues that are often compromised in traditional open and minimally invasive surgical approaches (▶ Fig. 84.1).

84.2 Key Principles

- AxiaLIF preserves the integrity of the paraspinal musculature, ligaments, posterior elements, as well as the anulus, which are all critical to the stability and function of the spine.
- The midline presacral corridor is an anatomical "safe zone" that is a largely aneural and avascular space beginning at the midline of S1–S2 and extending to the inferior end plate of S1, with a trajectory between the parietal fascia and the visceral fascia.
- The AxiaLIF implant provides a biomechanical advantage compared to traditional interbody cages with respect to flexion, extension, and lateral bending. The design helps to resist shear forces on the anterior column.
- AxiaLIF is a minimally invasive approach that has been shown in studies to be associated with minimal blood loss, reduced operating room time, and reduced length of hospital stay compared to other traditional lumbar fusion approaches (e.g., anterior lumbar interbody fusion [ALIF], posterior lumbar interbody fusion [PLIF]).

84.3 Expectations

The primary advantage of the presacral approach is the ability to preserve the integrity of the paraspinal musculature and ligaments, as well as the anulus, by utilizing the presacral corridor. Taking advantage of this, the expectation of the AxiaLIF procedure is to be able to achieve successful interbody fusion at the lumbosacral junction, with initial stabilization, and height restoration if desired, of the L5 and S1 vertebrae. AxiaLIF is intended to be performed in conjunction with posterior stabilization, typically via pedicle screw and rod fixation or in some circumstances via facet screw fixation.

84.4 Indications

The AxiaLIF system is intended to provide anterior stabilization of the L5–S1 (AxiaLIF 1L+) spinal segment as an adjunct to spinal fusion. This system is indicated for patients requiring fusion to treat pseudarthrosis, unsuccessful previous fusion, spinal stenosis, spondylolisthesis (grade 1 or 2), or degenerative disk disease as defined as back pain of diskogenic origin with degeneration of the disk confirmed by history and radiographic studies. The AxiaLIF system is also indicated for minimally invasive access to the anterior portion of the lower spine for assisting in the treatment of degeneration of the lumbar disk, performing lumbar diskectomy or for assistance in the performance of L5–S1 interbody fusion.

84.5 Contraindications

The AxiaLIF system is not intended to treat severe scoliosis, severe spondylolisthesis (grades 3 and 4), tumor, or trauma. Its usage is limited to anterior fixation of the lumbar spine at the L5–S1 level with supplemental posterior fixation.

84.6 Special Considerations

- With the AxiaLIF procedure, preoperative planning is critical. Detailed imaging studies, usually computed tomography (CT)

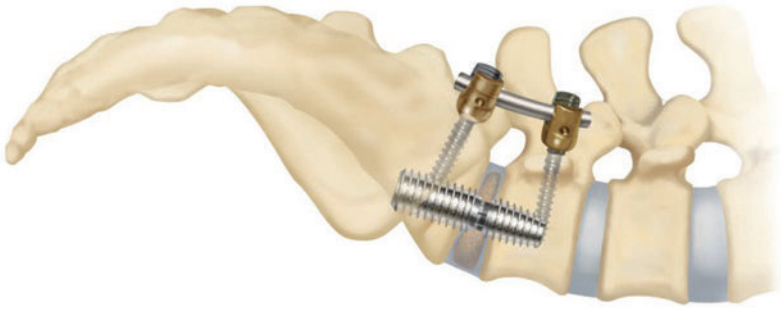

Fig. 84.1 AxiaLIF 1L+ with posterior fixation.

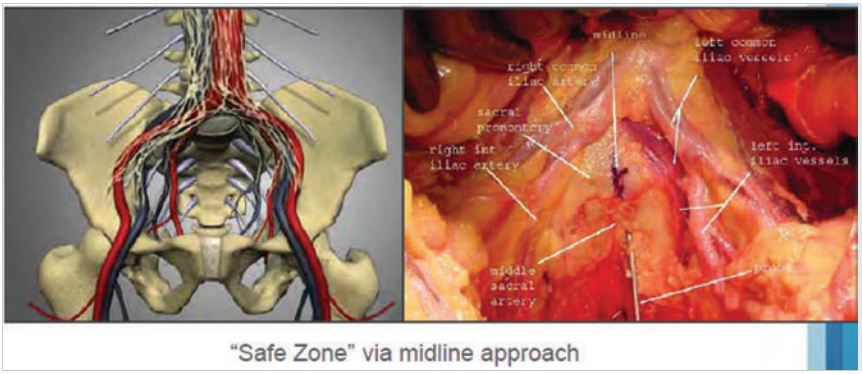

Fig. 84.2 Vascular structures present in the presacral space.

and magnetic resonance imaging (MRI), extending from L5 to the coccyx must be obtained. The surgeon must assess the presacral space for any unusual vascular anomalies or adhesions between the rectum and the sacrum or coccyx. Additionally, the surgeon must evaluate the trajectory on these images from the disk space to the tip of the coccyx. An alternative fusion technique should be selected if there are problems with trajectory, anatomical anomalies (e.g., curved or hooked sacrum), adhesions, or aberrant vasculature.

- A number of vascular structures are present in the presacral space, although most are avoided by maintaining a midline approach while traversing the sacrum. The primary exception is the middle sacral artery, which courses from the L5–S1 disk space to the coccyx. Parietal branches of the middle sacral artery proceed to the lateral sacral arteries; visceral branches of the middle sacral artery proceed to the posterior rectum. The path of the middle sacral artery has been shown to be extremely variable, however, and may not be encountered at all during the AxiaLIF procedure. This "safe zone" is devoid of neural or vascular structures that *may* limit the postoperative complications noted with the more traditional fusion procedures (▶ Fig. 84.2).
- Bowel injuries can occur with this technique, but the risk can be mitigated through careful technique and attention to safety measures built into the technique. When a bowel injury does occur, it is often either at the point of entry or at the sacral promontory. Incorporating the mini-open technique, finger dissection is used to create a pathway to the sacrum while gently pushing the rectum anteriorly from the mesorectal soft tissue plane, can help prevent these injuries. Preoperative bowel preparation is highly recommended, as this will facilitate dissection of the bowel and will also decrease the likelihood of infection in case of bowel perforation. Recently introduced additions to the instruments include a deployable bowel retractor that pushes soft tissue anteriorly, away from the working channel, and a conformable rubber-tipped tubular retractor that helps prevent gaps between the sacrum and the working instruments. These may help to further minimize risk of bowel perforations. If a bowel injury does occur, medical treatment (vs. surgical treatment) may be an option if the injury is identified early, although consultation with colorectal surgery is recommended.

84.7 Special Instructions, Positioning, and Anesthesia

Patients are positioned prone on a radiolucent operating table (typically a Jackson table with a sling), with sufficient support underneath the hips and shoulders to align the lower lumbar spine and sacrum in proper sagittal balance. The legs should be spread to allow for surgeon hand mobility during the procedure. No blankets, safety belts, or other objects should be placed above the knee, to maintain an open space between the legs. Depending on the patient's anatomy, gently taping the buttocks apart may facilitate access to the coccyx. An occlusive drape is placed across the buttocks just above the anus to exclude it from the sterile field. Prepping and draping should extend cephalad enough to include whatever posterior instrumentation will be placed. Biplanar fluoroscopy should be used throughout the procedure.

84.8 Tips, Pearls, and Lessons Learned

- Always template the trajectory *before* scheduling the procedure. Most access failures are due to failure of preoperative planning rather than intraoperative technique.
- Trajectory on the anteroposterior (AP) images should plan for implant placement between the pedicles. If the trajectory is too lateral, this may affect placement of pedicle screws later in the procedure or breeching of the lateral wall of the vertebral body. Docking of the K-wire is a critical point at which to ensure correct trajectory. This is easier if pedicle screws are already placed prior to initiating the AxiaLIF, allowing one to simply aim between the screws.
- Trajectory Adjustment during Procedure
  - If initial placement of the beveled guide pin is unsatisfactory, the guide pin should be removed and reinserted until the proper trajectory is achieved. Guide pin placement should err more posterior on the sacrum because the dilation process can cause the channel to "drift" anteriorly. As the guide pin is advanced, rotating the bevel anteriorly or posteriorly can help guide the pin in the correct sagittal direction. Frequent templating with a transparent overlay in front of the lateral fluoroscopy view will help ensure appropriate trajectory.

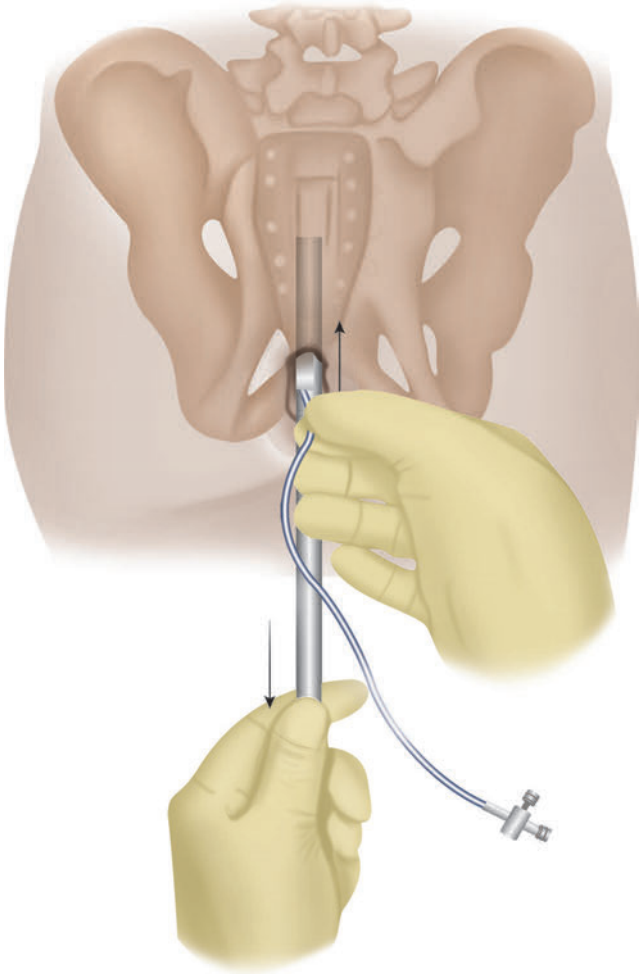

Fig. 84.3 Deployment of the bowel retractor.

- Sagittal trajectory can also be adjusted during each drilling step by raising or lowering one's hand.
- In rare cases where the correct trajectory cannot be achieved intraoperatively due to inability to raise one's hand enough, it is possible to use a Kerrison rongeur to widen the sacrococcygeal notch, but this must be done cautiously to avoid injuring nearby ligamentous, vascular, and/or neural structures.
- In osteoporotic patients, surgeons have opted to do more dilation in S1 and L5 than drilling. This helps to maintain implant fixation in the bone and to minimize subsidence. Also, in osteoporotic patients, it is recommended to be cautious with the amount of distraction created with the AxiaLIF implant as loss of fixation and anchor migration could occur.

- Use of the bowel retractor will help minimize bowel injuries (▶ Fig. 84.3).

84.9 Difficulties Encountered

- Many difficulties can be minimized by ensuring that an MRI scan to the tip of the coccyx has been completed preoperatively. Many patients with hooked sacrum or a transitional segment can be identified before surgery, thus allowing for necessary adjustments.
  - Hooked sacrum: Trajectory is the biggest difficulty. This has been mitigated by adjusting the incision site more superiorly. It should be noted that if the incision placement results in working through the sacrotuberous ligament, hand adjustments will encounter more resistance.
  - Transitional segment: May require special planning with the manufacturer for longer implants.
- Soft bone considerations: Less drilling and more dilation may be beneficial to provide better fixation of the implant in the bone. When drilling into L5, consider using the 9-mm drill instead of the 10.5-mm drill. In very osteoporotic bone, a drill is often unnecessary other than simply penetrating the inferior end plate—the rest of the channel can be created with a dilator alone. In addition, limiting the amount of distraction or utilizing the nondistracting implant is advisable to minimize subsidence and/or implant migration.
- Hard bone considerations: When implanting the AxiaLIF implant, hard bone may cause difficulty during bone dilation and during final implant placement. During initial bone dilation, avoid using excessive force when impacting the dilators, as sacral fracture is possible. During final implant placement, if excessive resistance is encountered the sacral channel can be prepared using the 12-mm drill, but do not drill through into L5, as it will create too large a channel for the L5-implant anchor.

84.10 Key Procedural Steps

- Use the "mini-open" technique with the coccyx as a backstop
  - Helps to minimize risk of bowel perforation at the incision site
- Use a blunt finger sweep or the blunt dissecting tool to open up the presacral space by mobilizing rectum from sacrum. This allows tactile feel of the proper dissection plane.
- Diskectomy is a two-staged process involving the use of deployable loop cutters and end plate rasps. Special focus should be placed on disk preparation as this step is the most crucial in the procedure. The diskectomy portion should not be rushed and should be expected to last at least 20 minutes. Improper or inadequate disk preparation may adversely affect the fusion process. End plate rasps are highly recommended, as they help to abrade the end plates of all cartilaginous material. During the disk preparation and depending on the trajectory established, the range of dissection could be affected. The use of fluoroscopy is essential to establish where the tips of the cutters and end plate rasps are, to avoid possible compromise of the anulus and to decrease the risk of graft extrusion due to a compromised anulus.

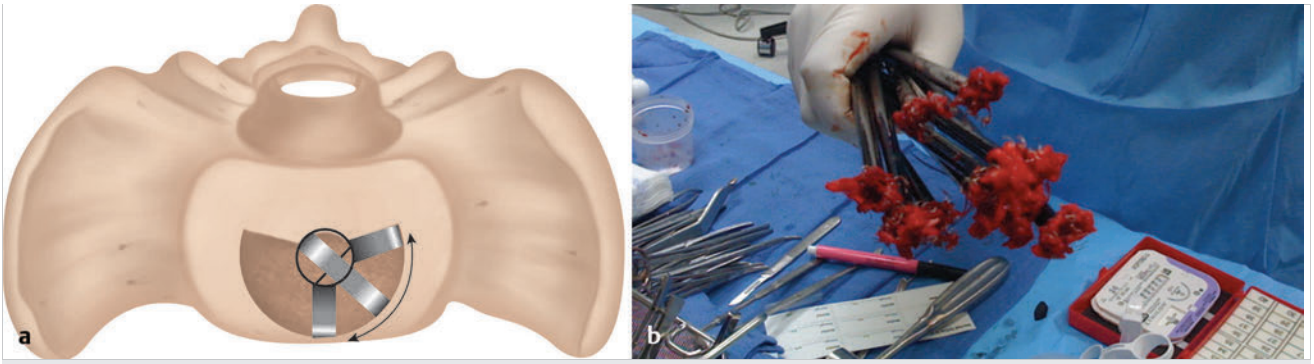

Fig. 84.4 **(a)** End plate preparation to debulk the nucleus pulposus and lightly abrade the end plate. **(b)** Tissue extractors are used to remove the disk and cartilaginous material loosened by the cutters.

- Always deploy the cutters and rasps anteriorly in the disk space to minimize inadvertent disruption of the posterior longitudinal ligament. If the working channel is placed more anterior, then deploy the instruments laterally. Sweeping of the curettes and rasps along the end plates typically should be from "2 p.m. to 10 p.m.," avoiding the posterior anulus, unless fluoroscopy clearly shows enough space to swing the instruments around posteriorly well in front of the posterior anulus. To further assist in achieving fusion, the end plate rasps should be used to denude the end plate cartilage down to bleeding bone (▶ Fig. 84.4a).
- Make generous use of the provided tissue extractors or "brushes," and optionally, laparoscopic irrigation and suction to help remove loose disk material from the disk space throughout the diskectomy portion of the procedure (▶ Fig. 84.4b). It is recommended to perform several rounds of alternating between curettes/rasps and brushes, and continue until little or no disk/cartilage can be extracted rather than stopping after a certain number or certain amount of time.

- Bone grafting should follow standard principles and incorporate materials that are osteoconductive, osteoinductive, and osteogenic.
  - Deploy graft material laterally and anteriorly. Avoid deploying posteriorly as it may cause graft extrusion and/or disk bulging, thus affecting the neural elements.
  - Do not force graft into the disk space once "back pressure" resistance has been encountered.
  - Do not rapidly force graft material into the disk space, as patient blood pressure may be affected.
- Use of the conformable tip tubular retractor during the procedure helps facilitate implant delivery and the soft tip minimizes risk of bowel perforation at the sacral promontory.
- During implant delivery, size the implant so there is tricortical purchase as this will help to reduce subsidence. A slightly tilted rod obtains better purchase and stability than a perfectly straight rod in the coronal plane.
  - Indirect decompression can be obtained after implant delivery with the AxiaLIF rod by "dialing in" the desired distraction across the L5–S1 interspace. In many cases, 1 to 3 mm of distraction is enough to reduce compression of the neural elements.
  - Use of a "neutral" or nondistracting AxiaLIF rod is an option for spondylolisthesis fixation after reducing the slip with pedicle screws, thus "pinning" the slip in place without axial distraction. This nondistracting rod is also simpler and faster to implant compared to the standard rod, and requires fewer instruments.
- Posterior fixation is indicated for all AxiaLIF cases. Choice of fixation is according to surgeon preference. Percutaneous facet screw fixation is an alternative to pedicle screws and rods, but is perhaps a less favorable choice for morbidly obese, osteoporotic, or highly physically active patients such as athletes. They are also not recommended for multilevel fixation, and are clearly contraindicated for isthmic spondylolisthesis.

84.11 Bailout, Rescue, and Salvage Procedures

In the event of a pseudarthrosis with the AxiaLIF device, several salvage options are available. One choice is simply placing a transforaminal lumbar interbody fusion (TLIF) or PLIF interbody cage within the disk space on either side of the rod, or even to place one or two cages alongside the rod from an anterior approach. In the event that the AxiaLIF implant needs to be removed (e.g., due to infection or gross migration), the manufacturer has developed a dedicated presacral retrieval kit to help facilitate the removal. Because the presacral approach utilizes a natural tissue plane scar tissue is minimal, thus allowing re-entry into the presacral space through the same paracoccygeal incision, and bluntly dissecting in the same manner as the index surgery. In some cases, bony overgrowth can make accessing the caudal end of the rod difficult, but actual extraction of the implant is usually quite fast and easy. As a third option, it is possible to access the implant through an ALIF approach, grasp it within the disk space, and back it out until it can be retrieved below the sacral promontory, then complete a standard ALIF procedure.

Pitfalls

- Do not operate on patients that have MRI evidence of adhesion between bowel and the sacrum. Similarly, avoid AxiaLIF in patients with blood vessels near the docking point on the sacrum to minimize risk of vascular complications.
- When establishing the initial guidewire placement, take the time to ensure proper trajectory. This will make the remaining steps of the procedure more efficient as you will minimize the need for difficult trajectory adjustments by raising or lowering your hand throughout the procedure.
- Utilize AP imaging to avoid a trajectory that will place the implant too close to the pedicles in L5. This could interfere with proper placement of a pedicle screw, or make AxiaLIF implant placement difficult when pedicle screws are already placed.
- Do not rush through the diskectomy. This is the most important part of the procedure and should take the most time to complete. Improper disk preparation can negatively impact the fusion process.
- Overpacking the disk space with bone grafting material can cause extrusion of disk and/or bone graft into the spinal canal and/or neuroforamen, producing postoperative neurologic symptoms. Stop the insertion of bone graft once resistance, or “back pressure” is felt with the bone graft inserter.
- Do not overdistract the implant, as overdistraction can lead to subsidence or intraoperative migration of the implant. Surgeons on average have applied distraction of 1 to 3 mm before the limitations of the anatomy (ligaments/anulus/posterior elements) provide resistance as felt through the distraction instruments.

85 Minimally Invasive Tubular Posterior Lumbar Far Lateral Diskectomy

Rishi Wadhwa, Hai Le, Rajiv Saigal, and Praveen Mummaneni

85.1 Description

Minimally invasive tubular lumbar far lateral diskectomy is a muscle-sparing procedure utilizing a tubular retractor placed in the Wiltse plane to access extraforaminal lateral disk herniations. The use of the tubular retractor allows for a small incision and minimizes disruption of the posterior paraspinal muscles that may limit postoperative pain and shorten hospitalization. Visualization through the tubular retractor is enhanced with use of an operating microscope.

85.2 Key Principles

Up to 12% of lumbar nerve root compression is due to far lateral lumbar disk herniations. A far lateral disk herniation has been defined as a disk herniation compressing the nerve root after it exits the foramen (i.e., lateral to the pedicle). It may be beneath or lateral to the facet joint.

The anatomical location of the far lateral disk herniation makes the approach somewhat challenging. Standard open approaches are commonly used, but often lead to a larger incision to access lateral enough to remove the disk.

As with any lumbar surgery, preoperative imaging studies including magnetic resonance imaging (MRI) to evaluate the neural elements is needed. Computed tomography (CT) to evaluate surrounding bony structures may be helpful as some of these disks may calcify. In addition, flexion–extension films to rule out instability should be obtained.

85.3 Expectations

The expectations of a minimally invasive tubular far lateral diskectomy should be removal of the compressing disk fragment and decompression of the nerve root, which allows for resolution of pain, weakness, and/or numbness.

85.4 Indications

Far lateral lumbar microdiskectomy is primarily indicated to treat primary or recurrent far lateral single-level lumbar disk herniation. Far lateral lumbar disk herniations (FLLDH) account for 12% of lumbar disk herniations and primarily affect L3–L4, L4–L5 (most common), and L5–S1. Clinically, up to 75% of patients will present with femoral nerve syndrome and 25% with sciatica. The radicular pain and symptoms are usually more severe compared to paracentral herniations. Patients with FLLDH who have failed a trial of conservative management (e.g., nonsteroidal anti-inflammatory drugs, physical therapy, and epidural or nerve root steroid injection) are surgical candidates.

85.5 Contraindications

Relative contraindications to minimally invasive far lateral lumbar microdiskectomy include those with concomitant mobile spondylolisthesis (that may require fusion) and central spinal stenosis (for which laminectomy is needed). Disk herniations medial to the pedicle are not accessible by a far lateral surgical approach, so preoperative imaging studies are important in correctly diagnosing FLLDH prior to surgery.

85.6 Special Considerations

Morbidly obese patients require a longer tube to access the disk. However, morbid obesity is not a contraindication to minimally invasive far lateral diskectomy, and these patients may benefit most due to the high reduction in soft tissue dissection compared to standard open approaches. Patients with both lateral stenosis from a far lateral herniated disk fragment and craniocaudal foraminal stenosis from a collapsed, degenerated disk may not achieve adequate relief from removal of disk fragments only. In addition, the procedure is best suited for patients with primarily a monoradiculopathic pattern of pain. If back pain is a significant component of the patient's clinical picture, they should be forewarned that diskectomy alone is unlikely to alleviate back pain symptoms. Special care should be taken with the scoliotic patient. In particular, considerable coronal plane deformity adds complexity to localization and interpretation of lateral fluoroscopy.

85.7 Special Instructions, Positioning, and Anesthesia

After induction with general anesthesia, the patient is positioned prone on a radiolucent table. The radiolucent table is necessary for obtaining the requisite anteroposterior (AP) and lateral fluoroscopic films for localization. A Wilson frame is optional, but may assist the decompression by creating segmental distraction. Pressure points should be well padded. The arms are brought cephalad into the "Superman" position and rested on padded arm boards. Neuromonitoring with electromyography and direct nerve stimulation may be helpful to identify the nerve.

85.8 Tips, Pearls, and Lessons Learned

- As with any minimally invasive surgical (MIS) approach, positioning and localization are key to the successful completion of the procedure. Extra time and care should be taken to make sure that the entry and docking sites are at the correct surgical level.

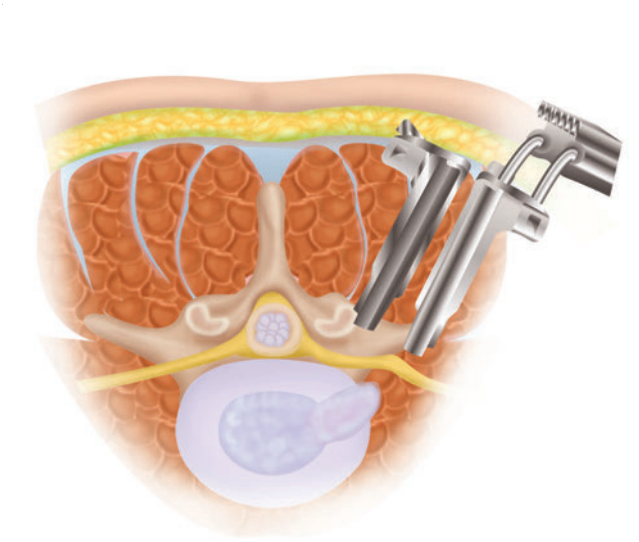

Fig. 85.1 Depiction of the axial plane of a tubular retractor used for access to the removal of an extraforaminal disk herniation.

- Use of minimally invasive tubular retractors from a posterior, paramedian approach minimizes osteoligamentous injury.
- Use of angled instruments is helpful in maintaining an adequate view through the small tubular window.
- The choice of surgical approach should be dictated by patient anatomy, pathology, and surgeon comfort. Minimally invasive far lateral diskectomy is more technically demanding that standard open approaches due to the limited field of view. The surgeon should obtain adequate specialty training and/or cadaver-based experience.
- A direct lateral minimally invasive approach may be a viable surgical option at the upper lumbar levels, but may not possible at the lumbosacral junction due to the position of the overlying iliac crest.

85.9 Difficulties Encountered

The learning curve for MIS cases is steep and the junior surgeon may find it easy to get lost without a standard open view of the usual anatomical landmarks. A combination of AP and lateral fluoroscopy should be utilized to corroborate the suspected anatomical location of the far lateral disk. It is imperative to obtain complete certainty of the surgical level prior to proceeding disk removal.

85.10 Key Procedural Steps

The key steps for this procedure are as follows: AP and lateral fluoroscopy is used to mark the medial border of the transverse processes (TPs) of the level cephalad to the target disk. Second, a 3-cm long incision is made 1 cm lateral to this site, allowing the angled trajectory needed to access the extraforaminal space. Next, a small fascial opening is made sharply and the sequential muscle dilation is done to create a muscle-splitting corridor for the tubular retractor system. Sequential dilators are then used, and the tubular retractor is positioned (we prefer a 22-mm working channel with an expandable tube). This tubular retractor is secured by an operating table mounted flexible arm (see ▶ Fig. 85.1, **Video 85.1**). The operating microscope is then brought in for visualization. The patient can be slightly rotated away from the surgeon to obtain better visualization. The muscle over the TP is dissected off with cautery, and the dissection is carried on further to expose the lateral pars and facet. The intratransverse ligament is removed as necessary to expose the exiting nerve root. A Woodson instrument is then used to feel the foramen from "outside-in" as well as the inferior pedicle. A nerve stimulator is often employed to identify the nerve root just superior to the disk. The level of surgery is again confirmed with lateral fluoroscopy. If further exposure is needed, bony removal of the lateral pars or lateral facet may be carried out with an angled bur. Next, the epidural veins are cauterized with bipolar electrocautery, followed by anulus identification and cruciate incision. Lastly, the disk is removed in a piecemeal fashion with Kerrison and pituitary rongeurs. Hemostasis and closure are done in the standard fashion.

85.11 Bailout, Rescue, and Salvage Procedures

In the event of not finding extruded disk material, fluoroscopy is warranted to confirm the correct level and position of surgery. If the sacral ala is blocking the tubular access for a L5–S1 far lateral disk, we advise using the bur to drill off a small amount of the iliac crest to create a working channel that will house the tube. Lastly, if the tube is docked too medially, excessive drilling into the facet joint may result in destabilization. Docking the tube too laterally may expose the psoas muscle lateral and deep to the far lateral disk herniation.

Pitfalls

- If the disk is not extraforaminal, excessive removal of the facet joint will potentially increase instability.
- Postoperative causalgia pain can occur by trauma to the dorsal root ganglion. This is usually self-limiting and resolves after a few weeks.

86 Minimally Invasive Posterior Transforaminal Lumbar Interbody Fusion

Rajiv Taliwal, Alexander T. Brothers, and Alexander R. Vaccaro

86.1 Description

A posterior transforaminal lumbar interbody fusion (TLIF) through a single posterior incision via a minimally invasive approach is used to achieve a 360-degree fusion with unilateral foraminal decompression along with disk height elevation. The procedure may be performed unilaterally or with instrumentation on both sides for added stability.

86.2 Key Principles

An anterior interbody fusion assists in restoring sagittal height and alignment and promotes bony healing with an increased surface area for fusion. A posterior tension band using instrumentation along with a posterolateral fusion enhances long-term stability. Direct decompression of neural elements can be performed unilaterally or bilaterally. The minimally invasive approach reduces collateral damage to the surrounding tissues and improves early recovery time.

86.3 Expectations

A unilateral approach allows for decompression with direct visualization of the exiting and traversing nerve roots. A direct view of the disk space and respective pedicles and transverse processes allows for ease of fusion.

86.4 Indications

This approach is utilized for single- or two-level stenosis and instability. It is especially useful for foraminal stenosis due to facet hypertrophy, recurrent lumbar disk herniation, segmental collapse, and coronal or sagittal imbalance.

86.5 Contraindications

Severe osteopenia or osteoporosis can limit the stability of applied internal fixation. The placement of an allograft, polymer, or metallic interbody spacer should be avoided in the setting of an infectious diskitis or abscess. Severe disk collapse or disk space autofusion may limit ability to open the disk space. Reducing a high-grade spondylolisthesis may place undue stretch on the exiting nerve; with inadequate reduction, the interbody graft may not seat fully into the disk space.

86.6 Special Considerations

Preserve midline structures as a functioning tension band. Focus on foraminal rather than central decompression. Fusion of anterior and posterior spinal elements requires adequate bony preparation and grafting materials; attempt to limit muscular dissection.

86.7 Special Instructions, Positioning, and Anesthesia

Position the patient prone on a Jackson table for anteroposterior and lateral fluoroscopic imaging, with the abdomen free from pressure. Drape widely to allow for a paraspinal approach. Make the incision about 2 cm off midline, then approach between the paraspinal musculature with blunt finger dissection or dilation of tubular retractors. Place screws first, then proceed with decompression and interbody fusion. Electromyography can be used for nerve monitoring and accuracy of screw placement.

86.8 Tips, Pearls, and Lessons Learned

Limit nerve retraction, which may be injured during retraction. Prefer wider facet resection to maximize the operative window and limit nerve stretch. The traversing and exiting nerves need to be directly visualized during graft placement. Excessive end plate manipulation can lead to graft subsidence. Try to avoid oversizing the interbody graft. Use the junctional normal disk space level as guide for disk-height restoration and graft size. Grafts placed centrally away from the apophyseal ring may have a higher chance of subsidence. Keep the interbody spacer near the periphery of the end plates preferably anteriorly to minimize subsidence.

86.9 Difficulties Encountered

Excessive bleeding may be encountered due to violation of the epidural veins. Be prepared with hemostatic agents and bipolar electrocautery for this event. Severe coronal deformity may be corrected with gradual distraction of screws and dilatation of disk space with sequential sizers. A dural tear or neurapraxia from overretraction or overcorrection of disk space height should be avoided.

86.10 Key Procedural Steps

Paraspinal incision must be properly placed to optimize screw angle and facet visualization. Expose from the transverse process to transverse process of the respective level. Be sure to identify the pars interarticularis and the facet joint. Pedicle screws should be placed at the level above and below by using bony anatomical landmarks of the transverse process and pars, or via fluoroscopic guidance. Perform facetectomy by starting laterally and working the decompression medially. The exiting nerve root will exit laterally, immediately below the cephalad transverse process, and should be avoided at all costs. Once the facet is resected, the exiting and traversing nerve roots can be easily visualized.

The diskectomy is performed by first making a small anular incision. A thorough diskectomy is preferred, removing as much disk as possible to optimize fusion surface. Minimize nerve retraction or irritation by excessive contact with instruments going in and out of the disk space. Limit excessive end plate preparation to avoid graft subsidence, and avoid over- or undersizing the interbody graft.

The interspace is then packed with as much cancellous bone as possible before insertion of the interbody spacer. Some distraction across screws prior to graft insertion may limit unnecessary trauma to the vertebral body end plates; however, avoid excessive distraction on the pedicle screws to avoid screw loosening. The graft is tapped into position while maintaining visualization of the nerve roots. Confirm graft placement with intraoperative biplanar imaging.

86.11 Bailout, Rescue, and Salvage Procedures

If visualization is inadequate via the minimally invasive approach, one may need to extend the incision for an open exposure. One can abandon the interbody fusion portion of the procedure and either perform a posterolateral fusion or perform a staged anterior or lateral interbody fusion.

Pitfalls

- Osteopenia can result in improper interbody graft fit or graft subsidence.
- Oversizing the graft can also lead to early failure from graft subsidence. An undersized graft can result in early graft extrusion.
- Screw loosening may result from excessive distraction during graft placement.
- Nerves can be injured from excessive traction, either during retraction or from excessive disk height elevation or deformity correction.
- A dural injury is difficult to repair with a minimal exposure and a hematoma may result in symptomatic neural compression due to the limited space available from the dissection for the blood to dissipate.

87 Percutaneous Cement Augmentation Techniques (Vertebroplasty, Kyphoplasty)

Gregory Gebauer

87.1 Description

Percutaneous cement augmentation (PCA) techniques are minimally invasive techniques for treating compression fractures of the spine due to osteoporosis, trauma, or lytic lesions. Vertebroplasty is performed by injecting bone cement (most commonly polymethylmethacrylate [PMMA]) into the fractured vertebral body (▶ Fig. 87.1). A kyphoplasty is performed by initially introducing a balloon to create a void within the bone into which the cement is injected (▶ Fig. 87.2). Cement augmentation has also been adapted to help improve pedicle screw fixation in patients with osteoporotic bone.

87.2 Key Principles

The injection of bone cement into the fractured vertebra provides mechanical stability to help reduce pain. The creation of a void during kyphoplasty allows for lower pressure injection of the cement and therefore a lower incidence of cement extravasation when compared to vertebroplasty. Additionally, a balloon tamp or other similar device may help to reduce the fracture and minimize the kyphotic deformity associated with these fractures, although the clinical significance of fracture reduction has yet to be determined.

87.3 Expectations

Compression fractures of the spine can be extremely painful. Although most nonpathologic fractures will go on to heal, the process can take weeks to months. Often this will decrease the mobility and activity of elderly patients, leading to deconditioning. In addition, many elderly patients do not tolerate narcotic pain medications, which can lead to delirium, constipation, and other complaints. Percutaneous cement augmentation provides a minimally invasive option for quick and effective pain relief.

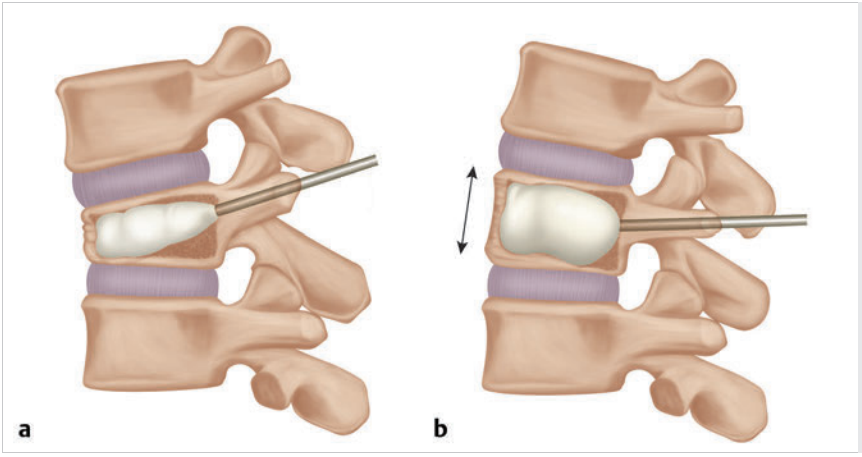

Fig. 87.1 **(a)** Lateral diagram showing inflatable balloon tamp is inserted into the vertebral body via a transpedicular approach. **(b)** Inflation of the balloon tamp elevates the vertebral end plates to achieve fracture reduction.

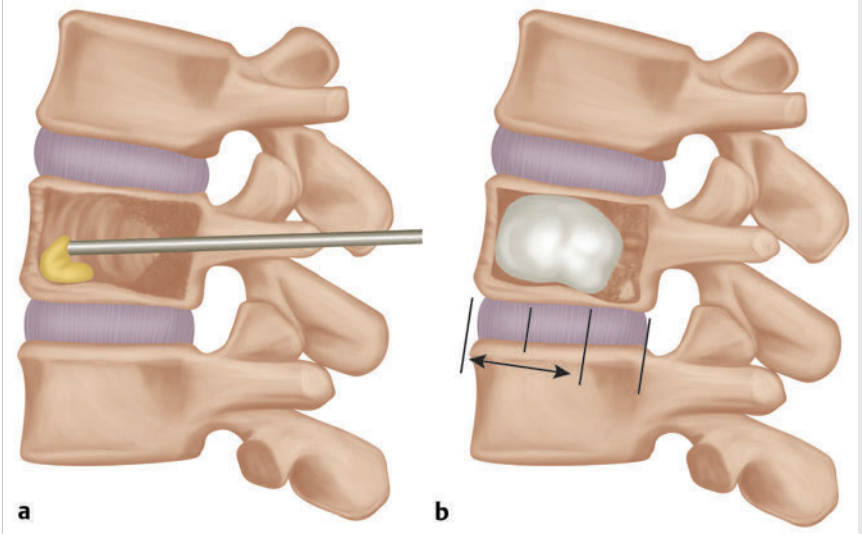

Fig. 87.2 **(a)** Lateral diagram showing injection of cement into cavity created by the balloon tamp. (b) Cement is filled until small appendages can be seen infiltrating the trabecular bone around the cavity. Cement volume should be greater than the volume of the balloon. The cement is kept in the anterior two-thirds of the vertebral body to minimize the risk of cement leaks through posterior wall defects or venous channels.

87.4 Indications

Percutaneous cement augmentation is indicated for painful compression fractures in the thoracic and lumbar spine stemming from osteoporotic insufficiency fractures, minor trauma, or certain pathologic fractures. Common causes of pathologic fractures include metastatic disease, multiple myeloma, and renal osteodystrophy. Percutaneous cement augmentation can be considered in the case of an impending pathologic fracture.

87.5 Contraindications

Percutaneous cement augmentation should not be performed in the setting of infection, solid tumors, healed fractures, or specific vascular lesions. It is not recommended in the setting of high-energy injury with associated posterior vertebral body injury. These techniques may be utilized if there is disruption of the posterior vertebral wall following low-energy trauma, but only with extreme care. Percutaneous cement augmentation should not be used if there is any compression of the neural elements or neurologic injury without a decompressive procedure also being performed. Percutaneous cement augmentation should be avoided until any coagulopathies are corrected. Patients should be medically optimized prior to cement augmentation.

87.6 Special Considerations

Magnetic resonance imaging (MRI) is the standard imaging modality in the setting of an acute compression fracture; it can assess both the morphology and the chronicity of the fracture. However, there are many patients who are not able to undergo MRI. In these patients, a computed tomography (CT) scan and a bone scan can be obtained. The CT scan can be used to assess fracture morphology. The bone scan can assess the chronicity of the fracture; however, this test is not without limitation. It can take up to a week after a fracture occurs for it to show up on a bone scan, leaving the potential for a false-negative test. Additionally, signal uptake on a bone scan can be seen within the vertebral body for up to a year after a fracture occurs, even after the healing process is nearly complete.

Prior to surgery, the morphology of the fracture should be carefully evaluated. Fractures with significant compression or vertebra plana may be hard to access with a cannula. In addition, any posterior vertebral wall involvement or retropulsed fragments should be noted as these may increase the possibility of posterior cement extravasation or further retropulsion of bony fragments. If PCA is to be performed on these patients, the cannula should be placed as anterior as possible and frequent fluoroscopic images should be obtained during the cement injection process. The injection of cement should be stopped immediately if any cement is noted to be tracking posteriorly.

Although osteoporosis is the most common cause of vertebral compression fractures, they can also be the result of pathologic processes within the bone. A biopsy sample of bone should be obtained as part of the augmentation procedure. This can lead to the diagnosis of a new cancer or may help determine if this is metastatic spread of an existing cancer.

Cement augmentation techniques can be adapted to supplement pedicle screw fixation during both open and minimally invasive surgeries. The pedicle is first cannulated and then palpated with a ball-tip probe to ensure that there are no breaches. If a kyphoplasty procedure is being performed a balloon catheter is then placed and inflated. Cement is then injected into the vertebral body followed by placement of a screw before the cement hardens. Alternatively, some surgeons may prefer to place the screw, remove it, then place cement, and then replace the screw. This allows for neuromonitoring to test the screw and for any adjustment to the screw position to be made before the cement hardens.

87.7 Special Instructions, Positioning, and Anesthesia

Positioning the patient in lordosis/extension may assist in postural reduction of a fracture. A radiolucent table should be used with care so the bed posts do not interfere with fluoroscopic imaging. For lower lumbar levels, the arms can be placed at 90 degrees to the body with the hands towards the head. For thoracic levels, tucking the arms at the sides may help with visualization. Care should be taken during positioning as patients with severe osteoporosis are at risk for other fractures including rib fractures.

General anesthesia, intravenous (IV) sedation, or local anesthesia can be used. The type of anesthesia used should be based on the patient's medical comorbidities, the expected difficulty or ease of accessing the fractured level, the number of fractures to be addressed, and the anesthesiologist's comfort level. If IV sedation or local anesthesia is used, the skin should first be anesthetized. A spinal needle can then be placed onto the periosteum where the trocar will be inserted and local anesthetic injected to provide for additional pain relief. If the patient is awake, additional pain may be noted during balloon expansion if a kyphoplasty is being performed.

The monomer component of PMMA can cause hypotension and cardiorespiratory collapse. The anesthesiologist should be alerted at the time of cement injection. In general, it is recommended to only augment three levels at one time; however, this risk must be balanced against the risks of a second anesthetic exposure. If more than three levels are indicated, there should be a pause during the surgery to minimize the effects of the monomer.

87.8 Tips, Pearls, and Lessons Learned

The use of biplanar fluoroscopy can be of significant help. Two fluoroscopes are used (▶ Fig. 87.3). One is positioned for a lateral view with the boom either under or over the patient. The boom is then rotated towards the patient's head to make room for the second fluoroscope, which is positioned for an anteroposterior (AP) view. It is often easier to rotate the bed to get true AP and lateral views rather than repositioning the patient. The use of two fluoroscopes allows the two images to be obtained independently and if needed simultaneously, rather than having to have one fluoroscope rotate between the two

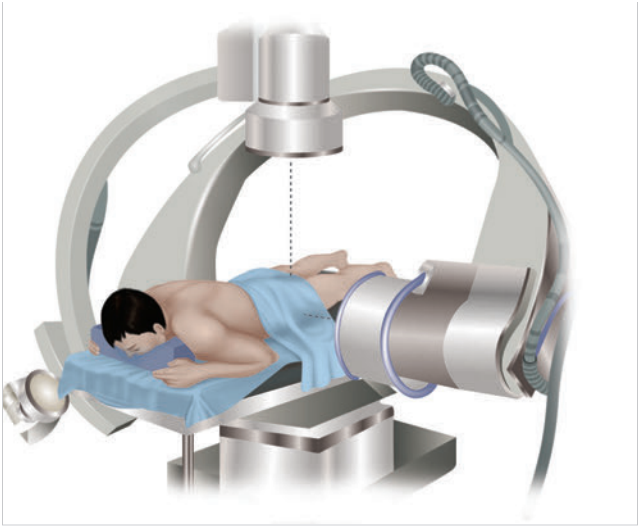

Fig. 87.3 Biplanar fluoroscopy is best accomplished with two simultaneous C-arms. The patient is placed prone on a well-padded, radiolucent table (e.g., Jackson flat table). The C-arm for the lateral image is brought in first (C-arm 1). By placing the arc over the top of the patient, the arc can be leaned over and away from the incoming C-arm used for the anteroposterior (AP) image. The C-arm for the AP image is brought in diagonally from the same side (C-arm 2). The surgeon stands on the opposite side of the C-arms. Entry of C-arm 2 in a diagonal fashion can make adjustments challenging. Thus, it is best to move the lateral C-arm 1 up slightly to provide adequate working room to obtain a true AP image of the target site. Once the AP image is captured, C-arm 2 is adjusted to obtain a true lateral image of the target site.

positions. The level of the fracture can also be confirmed independently on both images to ensure accuracy.

Treatment of multiple fractures can present a number of challenges. Not all the fractures may be visible on the fluoroscope in a single image. In this case it may be best to treat one fracture at a time and ensure that there is proper visualization on the fluoroscopic images. The cement may start to harden before all of the fractures can be addressed and additional batches of cement can be mixed if necessary. As a general rule, no more than three levels should be addressed at one time due to the risks of cement toxicity.

Severe collapsed fractures also present a challenge. Accessing the vertebral body may require careful cannula placement. Frequent images should be checked and small adjustments made to have the cannula enter at the midpoint of the remaining bone. If performing a kyphoplasty, the fracture has a tendency to collapse back down when the balloon is removed. There are two techniques that can help prevent this. Newer model balloon tamps (Kyphon, Medtronic) have been manufactured that can withstand the heat of cement as it cures. The collapsed vertebrae is cannulated with two tamps, one on each side. One balloon tamp is deflated and removed while the other is left in place. Cement is then inserted on the side in which the balloon tamp was removed and allowed to start to harden. The other balloon tamp is then withdrawn and the cement inserted on that side. If the newer model of balloon is not available, a small amount of cement is inserted before the balloons are placed. The balloon is then inflated causing the cement to expand and harden creating an eggshell around the balloon. The balloons are withdrawn and additional cement inserted.

87.9 Difficulties Encountered

Localization of the fractured level can be challenging. This is particularly true in the thoracic region. The correct level should be counted from a known landmark, such as the pelvis or a prior surgical site. Care should also be taken to note other old and healed compression fractures that the patient may have so that these are not confused with the current acute fracture. A lack of mineralization in osteoporotic bone can also complicate localization. This can also affect the surgical procedure by leading to incorrect placement of instruments and potentially to cement extravasation or neurologic injury. Experienced X-ray technicians and the use of columnization and magnification may help mitigate this. If adequate fluoroscopic images cannot be obtained the surgery should be aborted.

The curing time of PMMA is variable and may change based on the amount of agitation during mixing, the surrounding temperature and the type of cement used. This may cause the cement to harden before it can be inserted. This may be especially true when performing surgery on multiple levels. Additional batches of cement may need to be mixed.

87.10 Key Procedural Steps

After the administration of appropriate anesthesia, patients are positioned prone on the operating table. Local anesthetic can be used, especially if the patient is receiving sedation rather than general anesthesia. Although the procedure can be performed with a single fluoroscope, the use of biplanar imaging can greatly facilitate the procedure. The level to be operated on should then be localized. This may be relatively simple for solitary fractures with clear compression. For less obvious fractures, the level should be counted from known landmarks, such as the sacrum, prior surgical hardware, or prior cement augmentation.

Once localized, the patient and the fluoroscope should be adjusted to have clear AP and lateral views of the fractured vertebrae. On the lateral view the pedicles should overlap and the posterior vertebral wall should be a single line (a double line may be present if there is rotation of the vertebral body). On the AP view both pedicles should be visible, they should be equidistant from the lateral vertebral body walls, and the spinous process should be centered between them. Fractures with asymmetric collapse may make getting true AP and lateral views difficult, in which case the surgeon should use his or her judgment to obtain the best possible image.

For larger pedicles, a transpedicular approach is most appropriate. An incision is made approximately 1 cm lateral to each pedicle. The trocars are inserted and docked just lateral to the pedicle and at the midpoint of the transverse process. The trocar is angled slightly medially and a hammer is then used to gentle tap the trocar into the pedicle, with care taken not to cross the medial wall of the pedicle on the AP view before entering into the vertebral body on the lateral view. Frequent images should be obtained and the trajectory adjusted as needed during insertion. Often, a transpedicular approach

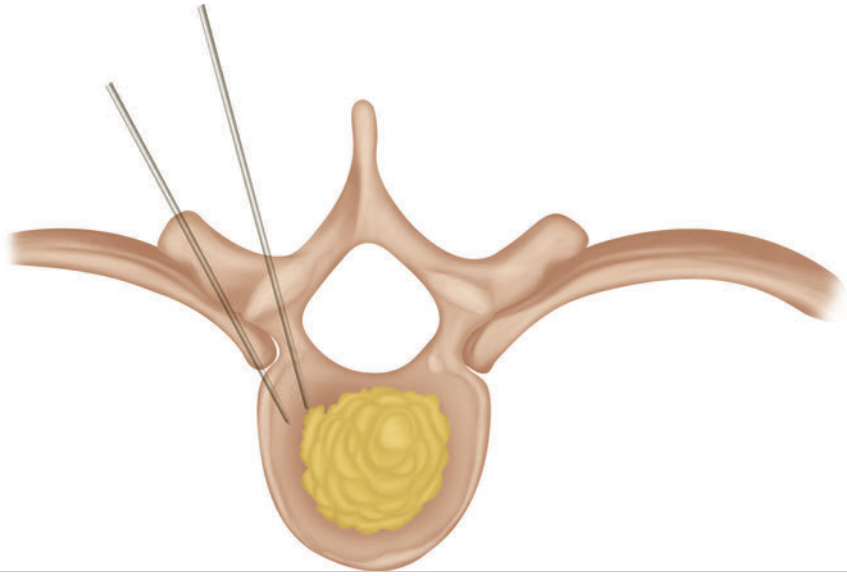

Fig. 87.4 Superior view of vertebroplasty, using pedicular and parapedicular approaches.

requires placement of bilateral cannulas; however, unilateral placement has been described and can be considered if the cannula is placed medial enough.

For smaller pedicles, such as those commonly encountered in the upper thoracic region, an extrapedicular approach may be more appropriate. Here an incision made approximately 2 to 3 cm lateral and 1 to 2 cm cephalad to the pedicle. The trocar is inserted and maneuvered over the rib and onto the lateral portion of the vertebral body. The entry point should be at the superior and posterior corner of the vertebral body, along the edge of the pedicle and at or slightly anterior to the posterior vertebral wall. A 45-degree beveled trocar may help to direct the trocar into the vertebral body. This approach generally allows for a more medial trajectory and may allow the procedure to be performed using only a unilateral approach (▶ Fig. 87.4).

Once the trocars are placed, the inner needle is removed and the working cannula is left in place. A biopsy sample can then be obtained. The use of a syringe on the back of the biopsy needle may provide some suction and help with the removal of a bone sample.

For vertebroplasty, the trocar and working cannulas are generally placed in the anterior one-third of the vertebral body. Low-viscosity cement is then injected into the vertebral body. Frequent fluoroscopic images should be obtained and care taken to observe for any extravasation.

For kyphoplasty, the trocars are generally inserted 2 to 3 mm past the posterior wall and into the vertebral body. Depending on the technique used, guidewires can then be advanced into the vertebral body and overdrilled to allow for balloon placement. Alternatively, a hand drill can be used without a guidewire. In either case, once the drill is removed, the balloons are placed. The balloons are then inflated. The surgeon should be familiar with the type of balloon used as there are differences in the size of the balloon and the pressure it can withstand before breaking. During balloon inflation, frequent fluoroscopic images should be obtained to ensure that there is gentle expansion of the fracture in terms of vertical height and that the balloon does not focally extrude out of the vertebrae and that no bone fragments are pushed posteriorly into the spinal canal. The balloons are then removed and cement is injected into the vertebral body under low pressure with care to avoid cement extravasation. Generally, small amounts of cement are injected followed by AP and lateral fluoro images to ensure that no cement leakage has occurred. Ideally, the amount of cement injected should be slightly greater than the volume in which the balloons were inflated. This allows for some interdigitation of the cement into cancellous bone, "locking in" the cement.

The cement is allowed to harden and the cannulas are withdrawn. The incisions can be closed with suture, Steri-Strips (3M), or Dermabond (Ethicon) according to the surgeon's preference.

87.11 Bailout, Rescue, and Salvage Procedures

If cement is noted to be extravasating during a vertebroplasty, the injection should be stopped immediately. The cement can be allowed to harden and then the cannula is repositioned and a second attempt at cement injection can be performed.

Cortical breaches can occur during balloon inflation when performing kyphoplasty. This can potentially lead to extravasation of cement outside of the vertebra. To prevent this, an eggshell mantle of cement can be placed. The balloon is first removed from the vertebra and a small among of cement is then inserted. The balloon is reinserted and then gently inflated so that it presses up again the vertebral wall. The cement is allowed to harden and the balloon withdrawn. Additional cement can then be inserted.

Higher rates of cement extravasation can be expected during vertebroplasty than during kyphoplasty; however, most cases are inconsequential. If cement is suspected of entering into the spinal canal a careful neurologic exam should be performed after the patient wakes up. If there are any new deficits, consideration for immediate surgical decompression should be entertained. Cement can occasionally enter into the venous system, potentially causing a cement embolism. These patients may need to be kept intubated followed by appropriate pulmonary and cardiothoracic consultations.

Pitfalls

- Incorrect level identification
- Poor visualization on fluoroscopic imaging due to osteoporosis
- Pulmonary compromise due to vascular cement embolization
- Cement extravasation, especially into the neural foramen or spinal canal
- Adjacent level fracture

88 Minimally Disruptive Approach to the Lumbar Spine: Transpsoas Lateral Lumbar Interbody Fusion

M. A. Khaleel and A. P. White

88.1 Description

Lateral lumbar interbody fusion (LLIF) is performed through a retroperitoneal transpsoas approach. This approach has gained popularity as it may offer certain advantages over alternative anterior and posterior approaches to the interbody space. Lateral lumbar interbody fusion has been associated with excellent interbody reconstruction and fusion, short hospital stays, and generally low complication rates. Care must be taken, however, to avoid injury to the lumbosacral plexus, which is one of the most common postoperative problems, particularly when operating at L4/L5.

88.2 Key Principles

The lateral approach, as compared to anterior approaches, limits the mobilization of abdominal contents and vasculature. This may decrease the risk of postoperative ileus, vascular injuries, and sympathetic plexus injuries, as compared to a traditional anterior lumbar interbody fusion (ALIF) through a retroperitoneal approach. Generous access to the interbody space is achieved with a LLIF, however, allowing for meticulous end plate preparation and fusion similar to ALIF. Interbody reconstruction is typically superior to that achieved by posterior interbody (transforaminal lumbar interbody fusion [TLIF], posterior lumbar interbody fusion [PLIF]) techniques, with the laterally placed device spanning the apophyseal ring and marginal cortex. Furthermore, by leaving the anterior and posterior longitudinal ligaments intact, segmental stability is maintained, while allowing powerful sagittal and coronal deformity correction via the placement of appropriately sized grafts.

88.3 Expectations

Fusion rates of up to 97% have been reported for the lateral interbody fusion. This minimally invasive approach is associated with short operating room times, low blood loss, short hospital stays, and improvement in pain and functional outcome scores. In some cases, the indirect decompression afforded by the procedure may also provide clinically adequate improvement of stenosis.

All patients should expect transient postoperative hip flexor weakness, related to the dissection through the psoas. Patients should also be informed of the significant likelihood of transient anterior thigh numbness, and the relatively low likelihood of transient quadriceps weakness. These risks may be decreased with use of motor evoked potential (MEP) neuromonitoring, short psoas retraction times, and gentle handling of the psoas, including maintenance of hemostasis.

88.4 Indications

The indications for lateral lumbar interbody fusion are similar to those for other interbody fusion procedures. This includes recurrent stenosis, trauma, tumors, infections, pseudarthrosis, adjacent segment disease, and deformities.

Indirect decompression of the neural elements can be achieved in some cases, such as in dynamic isthmic spondylolisthesis, where correction of the segmental deformity adequately resolves the cause of the stenosis. Preservation of the posterior and anterior longitudinal ligaments allows for reduction of segmental deformities through ligamentotaxis, employed through the placement of a large interbody device. Lateral interbody fusion techniques also offer powerful deformity correction of degenerative scoliosis, through the placement of an interbody device that spans the strong apophyseal ring and lateral vertebral cortex.

The lateral approach may provide a minimally invasive option to potentially address an adjacent psoas abscess and debride infected material within the disk space before placing an interbody graft such as iliac crest autograft. The decreased blood loss and morbidity is particularly a benefit in the setting of spinal infection, where many patients may have concurrent systemic disease such as diabetes, cirrhosis, or liver failure.

We have also found the direct lateral approach to be very useful when prior surgery or current pathologies make posterior or anterior approaches more difficult or a higher risk.

88.5 Contraindications

Retroperitoneal adhesions from prior surgery may prevent safe exposure. Aberrant retroperitoneal anatomy such as renal deformities may also preclude lateral access. Severe deformities associated with significant vertebral rotation can position the lumbosacral plexus or the retroperitoneal vessels over the lateral access corridor. Similarly, spondylolisthesis over grade 2 can be difficult to treat because the lateral aspect of the interbody space can be quite small: Graft placement may be difficult.

Performing transpsoas fusion at certain levels can be difficult; the iliac crest typically limits lateral access to L5/S1, and can compromise the access to L4/L5 in some patients. When there is a coronal deformity at the lumbosacral junction, L4/L5 can usually be reached by only one side (from the convexity). The ribs may limit access to thoracolumbar levels, but the thoracic cavity may be successfully accessed to treat thoracic and thoracolumbar spine pathology.

The largest fraction of postoperative adverse thigh symptoms has occurred when operating at L4/L5. Although there are many techniques available to help reduce these risks, many surgeons have elected to circumvent these risks by performing posterior or anterior interbody procedures at L4/L5 (and L5/S1) instead of a LLIF.

88.6 Special Considerations

Preoperative standing radiographs are used to evaluate the anatomy and alignment relevant to the lateral approach; high

iliac crests or low lying, long ribs may limit access. Coronal alignment can dictate the preferred side of the approach. In cases of scoliosis and coronal plane deformity, the surgeon must choose to approach the spine from the concavity or the convexity of the curve. Approach from the convexity may present easier access to the disk; this is particularly useful in single-level fusions. In multiple-level fusions, however, approach from the concavity may allow multiple levels to be addressed through a single small incision. Obliquity of the L4/L5 disk space must be noted, as this will dictate the side of approach based on the obstruction by the iliac crest.

The location and morphology of relevant retroperitoneal anatomy should be reviewed on magnetic resonance imaging (MRI) or computed tomography (CT). The preferred side of the approach may be directed by the location of the major abdominal vessels, and by the location and size of the psoas muscle. When there is psoas asymmetry related to deformity or other factors, it is preferred to traverse less psoas muscle, and also to traverse it more anteriorly; this may reduce trauma to the muscle and may also reduce the risk of postoperative adverse thigh symptoms. The roots of the lumbar plexus traverse from dorsal to ventral as they descend within the psoas. This contributes to the relative risks of neural injury at L4–L5. When the psoas is atypically anterior or atypically large, this risk may be increased.

Plain radiographs and CT may also provide an assessment of disk space ankylosis or bridging osteophytes, which may affect the approach from either side. Additionally, if CT or radiographs demonstrate posterior element fusion, a LLIF may be contraindicated. Applying powerful interbody distraction upon the robust sclerotic apophysis in this scenario has caused catastrophic bilateral pedicle fracture in the past.

88.7 Special Instructions, Positioning, and Anesthesia

The patient should be placed in a true lateral position on a radiolucent articulating table. The operative vertebrae are oriented such that a cross-table X-ray (parallel to the floor) produces a true posteroanterior (PA) image and a through-table X-ray (beam parallel to the wall) produces a true lateral image. The hips and knees are flexed to ease tension on the psoas, the lumbar plexus, and on the sciatic and femoral nerves. The lateral position allows the abdomen to fall anterior and contralateral, even in large patients, opening the retroperitoneal space. An axillary roll is placed and all pressure points are padded. The iliac crest is positioned at the “break” in the table and the pelvis is secured to the table below the “break” with 3-inch (nonelastic) cloth tape. The ipsilateral lower extremity is secured with tape from the greater trochanter, over the lateral femoral condyle, and to the edge of the table. Another band of tape is placed from the lateral femoral condyle to the lateral malleolus and to the other edge of the table, with care to avoid compression of the peroneal nerve just posterior to the proximal fibula. Some industry technique guides depict a less-favorable position with tape compressing the peroneal nerve. The table is gently flexed to open the space between the iliac crest and the rib cage. This is typically achieved with a small degree of bending, however, maintaining a safe and comfortable position. Significant bending is typically not required, and may increase the risk of positioning related complications. Tape is then used to secure the chest to the table.

The C-arm is used to confirm true lateral position described above, before draping. Adjust the table (patient) and not the C-arm, so that the vertebrae are orthogonal to the walls and floor. This may reduce the risk of inadvertently traversing posteriorly (into spinal canal and contralateral foramen) or anteriorly (into vessels). These complications have been described, and with catastrophic consequence.

The anesthetic plan should be discussed among the surgeon, anesthesiologist, and neuromonitoring technician. It is useful to use multimode monitoring, including MEP; this requires limited cortical suppression and no neuromuscular paralysis.

88.8 Tips, Pearls, and Lessons Learned

The table orientation should be adjusted (primarily in two modes) to obtain true anteroposterior (AP) and lateral images with the C-arm projecting parallel to the floor and parallel to the walls, respectively. These two modes are (first) rotation of the table “airplane” to get a true cross-table AP, then head up / head down (Trendelenburg / reverse Trendelenburg) to get a true lateral. Keeping the angle of the C-arm projection orthogonal to the floor allows the surgeon to work perpendicular to the floor at all times and avoid straying anterior toward the retroperitoneal vessels or posterior toward the neural elements. If a single C-arm is used, this well-oriented position of the table allows for easy transition from AP to lateral fluoroscopy.

Although a transverse incision parallel to Langer’s lines is more cosmetic and can provide access to multiple levels, a longitudinal incision may be needed, using separate approaches through the fascia and abdominal musculature.

The target for the initial dilator should typically be just anterior to the center of the disk. Anterior bias favors lordosis, and posterior bias favors foramen height restoration. Anterior bias may reduce the risk of nerve complications. Do not open the retractor unless required. It is safer to work through a smaller portal. Expeditious surgery is also safer than prolonged surgery.

88.8.1 Neuromonitoring

Despite routine neuromonitoring use, neurologic complications occur with regular frequency during transpsoas surgery, particularly at L4/L5. Most postoperative weakness and numbness are transient, but even transient quadriceps weakness is associated with significant functional morbidity. Some injuries have been permanent. Because the current (electromyography [EMG]) technique has been virtually blind to most of these injuries, we have developed an alternative neuromonitoring technique for an LLIF.

There are two distinct mechanisms of nerve injury during a LLIF. The first is a direct and instantaneous injury to a traversing nerve, such as that caused by placing the retractor or other instrument directly upon a nerve. In contrast, the second mechanism is an indirect and progressive injury. This is related to prolonged compression of the lumbosacral nerves between the posterior retractor blade and the transverse process

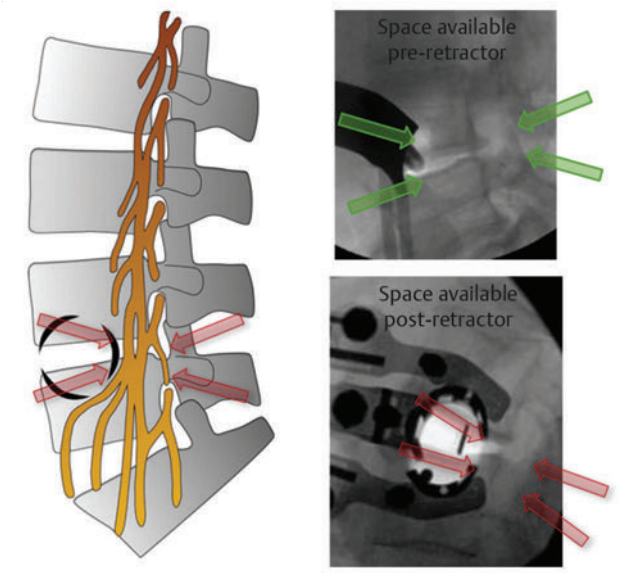

Fig. 88.1 Prolonged compression of the lumbosacral nerves between the posterior retractor blade and the transverse process may cause indirect, progressive injury.

(▶ Fig. 88.1). This mechanism may be more clinically relevant and may account for postoperative deficits more frequently. Some authors have observed that longer surgical times are related to a higher likelihood of injury.

Spontaneous or mechanically elicited EMG monitoring is sensitive for the first type of direct nerve injury mechanism. This is because uninjured nerves will depolarize on stimulation by the dilator or retractor, resulting in an EMG response. In contrast, spontaneous EMG monitoring is less sensitive to the second (progressive compression) mechanism of injury, accounting for many false-negative outcomes. This has a neurophysiological basis; gradual and progressive compression of nerve root is unlikely to incite neurotonic firing. This may be the reason why many reported cases of clinically significant neurologic injury following a LLIF have gone undetected on EMG monitoring.

Motor evoked potential monitoring, however, can detect prolonged compression injuries that do not elicit a depolarization. We use multimodal neuromonitoring, including spontaneous EMG (sEMG), triggered EMG (tEMG), and MEP. Subdermal needle electrodes are used in seven muscles on the operative side: iliopsoas, adductor longus, vastus medialis, vastus lateralis, anterior tibialis, gastrocnemius, and abductor hallucis. Muscles with potentially redundant innervation are used to ensure thorough monitoring of the lumbar plexus. Control recordings are also obtained on the contralateral side in four muscles: vastus medialis, vastus lateralis, anterior tibialis, and gastrocnemius. In male patients, the cremaster muscle is monitored with a subdermal needle electrode.

We use an 80% MEP signal reduction criterion for defining an alert. With this, we have not encountered a false-negative result, and we have identified injuries that were not detected by EMG. Although normal MEP cannot entirely preclude a nerve injury, the addition of MEP to EMG may improve the sensitivity of nerve root monitoring during LLIF. We recommend that the retractor be released following an MEP alert. An attempt can be made to reposition the retractor if MEP returns after relaxing the retraction. The opportunity to make this intervention may reduce the severity of the injury that is occurring at that moment, as opposed to the alternative, which is to continue to cause or exacerbate the injury that is ongoing due to compression of the neural elements. These injuries, if intervened upon, may be limited in severity and even be potentially reversible.

88.9 Difficulties Encountered

Patient positioning is critical to obtaining the true PA and lateral fluoroscopic images that are needed to maintain orientation, and avoid inadvertent excursions into the (posterior) foramen and canal or (anterior) retroperitoneal vessels. If the projection has been compromised, the case should be paused to adjust the table for a corrected image. In multiple-level surgeries, particularly with scoliosis, it is helpful to address peripheral levels first, so that the center levels remain accessible after correcting the more cranial or caudal segments of the deformity. Done in the opposite order, peripheral levels may become increasingly difficult to access.

88.10 Key Procedural Steps (Video 88.1)

88.10.1 Exposure

A metallic marker and lateral fluoroscopy is used to mark the skin incision. A 3- to 4-cm incision is made in line with the disk. The external oblique, internal oblique, and transversalis muscles are sequentially dissected in line with their respective fibers under direct visualization. Hand-held retractors are used to visualize the transversalis fascia, which is penetrated with blunt dissection to reveal the retroperitoneal fat. The index digit sweeps the fat anteriorly and palpates the posterior quadratus lumborum and then the transverse process. Wylie vein retractors are placed such that the space can be inspected, including the lateral surface of the psoas and any adjacent structures such as the ureter, and genitofemoral nerve. If retroperitoneal fat or peritoneum is observed, this must be mobilized anteriorly before proceeding with the retractor placement. The opportunity to carefully inspect the space is one of the critical advantages to the single incision "direct visualization" approach.

The psoas muscle sheath is opened with a long Metzenbaum scissor, gently separating the ventral from dorsal fibers. The first dilator is placed through this interval, upon the lateral disk space, with direct visualization and AP (cross-table) fluoroscopic guidance. Gently separating the fibers of the psoas with the Metzenbaum scissors can be helpful; we have found this to be associated with better and less traumatic dilation/retraction of the psoas. A triggered EMG lead is attached to the dilator, and stimulated to assess for adjacent neurologic structures. The dilator can be rotated to provide directionality to the stimulation (▶ Fig. 88.2). In the event of a neuromonitoring alert with placement of the initial dilator, the dilator may be placed more anteriorly and still provide adequate exposure.

Once a safe position is confirmed, a guidewire (or the first dilator itself) may be inserted into the disk space. Passing the

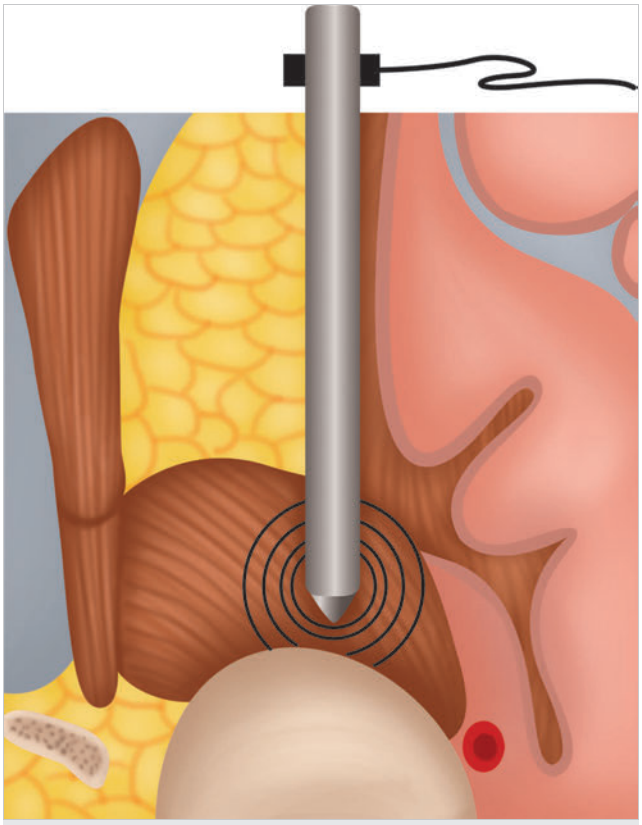

Fig. 88.2 With the triggered EMG lead attached, the dilator can be rotated 360 degrees to provide directionality to the stimulation

first dilator directly into the interbody space can help establish a retractor position roughly parallel to the end plates. A lateral image confirms the AP position at the center of the disk or somewhat more anterior, depending on the level and the goals of the interbody reconstruction. As discussed above, anterior positions favor lordosis, whereas posterior positions favor foramen and canal restoration.

Although some authors have proposed that there is a "safe working zone," other investigations (and clinical experience) have definitively refuted this. There is no reliable "safe working zone" that will guarantee safety and eliminate postoperative thigh symptoms, particularly at L4/L5. While docking the retractor just anterior to the middisk is advised, to help reduce the risk of encountering nerves, this alone cannot be expected to eliminate the risk of nerve injury.

Subsequent sequential dilation provides for placement of the retractor. The retractor is secured to the table, and its position is confirmed with biplanar images. A ball-tipped stimulating (EMG) probe may be used within the exposed field to assess for neurologic structures. A bayonetted Penfield elevator may be used to mobilize the muscle fibers and further expose the disk space.

88.10.2 Anulotomy and End-Plate Preparation

A 2-cm box anulotomy is performed with a bayoneted blade. Bayonetted curettes, pituitary rongeurs, and rasps are used for

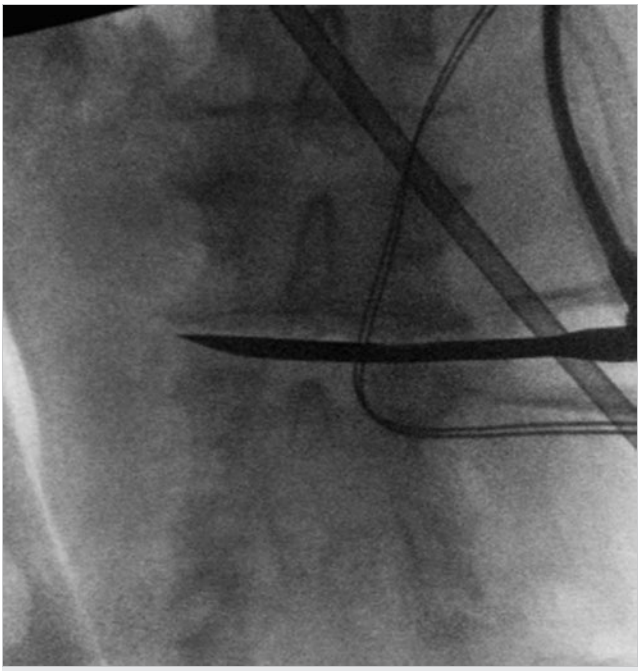

Fig. 88.3 A Cobb elevator is passed along the endplate to perform contralateral release of the annulus.

diskectomy. A Cobb elevator is inserted along the end plate to perform contralateral anulotomy, separating the Sharpey's fibers from both the cranial and caudal end plates under fluoroscopic guidance (▶ Fig. 88.3). This is required to achieve a balanced release and to create a balanced interbody reconstruction.

88.10.3 Insertion of Implant

Trial implants are placed to size the implant and to symmetrically distract the disk space. After removal of the trial, the interbody space is typically more open and more readily visualized; as such, a more complete diskectomy can be finalized. An implant with bone graft or substitute may be placed, spanning the entire disk space, overlying both sides of the strong ring apophysis, marginal cortex, and lateral osteophytes. This is confirmed with AP imaging; the implant should span at least to the lateral aspect of the pedicles (▶ Fig. 88.4).

88.10.4 Closing

Hemostasis within the psoas should be confirmed. Local coagulant such as SURGIFLO (Ethicon) can be helpful. This, as well as the placement of local steroid within the muscle, may help reduce postoperative psoas pain and dysfunction. The wound is closed in layers. Approximation of the muscle layers will help prevent hernia. Fascia and skin are close in the standard fashion.

88.11 Bailout, Rescue, and Salvage Procedures

If the implant needs to be removed or withdrawn, the inserter may be reattached. It is recommended to prep and drape a wide

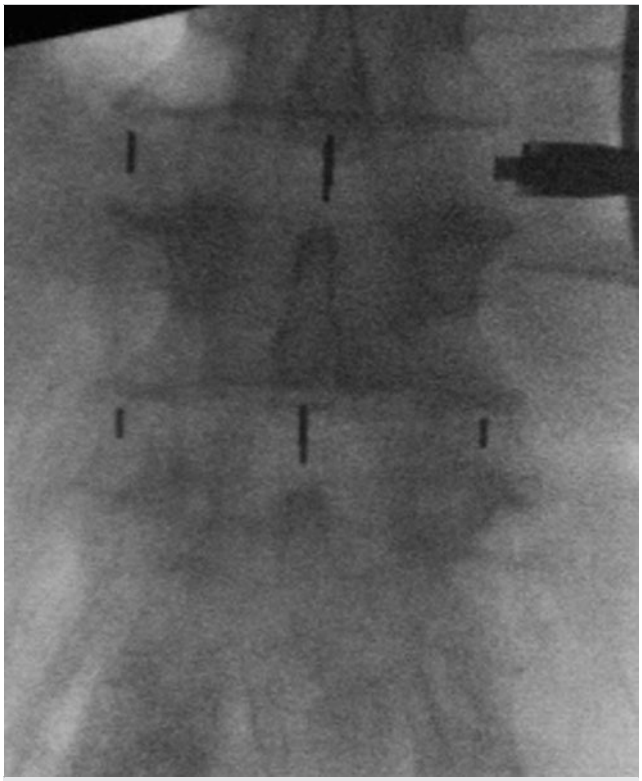

Fig. 88.4 The implant should traverse past the lateral aspect of the pedicle on AP imaging to ensure that it spans the apophyseal ring and marginal cortex.

surgical field. Wide anterior draping allows for expeditious anterior retroperitoneal exposure in the event of vascular or peritoneal injury. Wide posterior draping allows for pedicle screw instrumentation in the lateral position. If the anterior longitudinal ligament (ALL) is violated or ruptured by the placement of too large an implant or if the end plates are violated during preparation, the integrity of the construct may be compromised. Supplemental instrumentation may be required in such cases.

Pitfalls

- Overstuffing the disk space may disrupt the ALL or cause fracture. Conversely, using too short an implant may lead to subsidence. It is important that the contralateral anulus be released with the Cobb so that the implant can traverse the entire disk space and support the strong ring apophysis. Asymmetric insertion can lead to coronal plane deformity.
- Expeditious surgery is important; prolonged retraction will predispose to psoas-related and nerve-related complications. Additionally, proper hemostasis within the psoas upon removal of the retractor may help decrease the risk of hematoma and associated pain and numbness. Bipolar electrocautery and sintered Gelfoam (Pfizer Pharmaceuticals) may be helpful. Local steroid may also reduce postoperative psoas irritation.

89 Percutaneous Lumbar Pedicle Screw Fixation

John H. Peloza, Paul W. Millhouse, Gregory D. Schroeder, and Alexander R. Vaccaro

89.1 Description

Lumbar percutaneous pedicle screw fixation has many advantages over other fixation techniques. Pedicle screw fixation provides the most rigid three-column stability to the lumbar spine without compromising the neurovascular or visceral structures. Pedicle screws can be applied in the absence of lamina or facet joints and are utilized to reduce deformities, stabilize instabilities, and support interbody or anterior implants. Percutaneous pedicle screw systems offer the advantages of the open pedicle screw systems without the exposure-related muscle damage. Compared with traditional open techniques, the minimally invasive techniques may allow a decrease in blood loss, postoperative pain, and hospital length of stay.

89.2 Key Principles

The surgeon must take into account the following key points to safely implant percutaneous lumbar pedicle screws:

- Thorough knowledge of lumbar spine anatomy, particularly the pedicle anatomy, as the normal anatomical landmarks are not visible
- Patient positioning on the operating room table
- Routine use of fluoroscopy
- Routine use of intraoperative pedicle screw monitoring
- Use of computer navigation imaging
- Thorough knowledge of the particular implant system utilized, with the ability to trouble shoot intraoperative problems

89.3 Expectations

Minimally invasive spine surgery may lead to a decrease in iatrogenic soft tissue injuries resulting in decreased blood loss, less early postoperative pain, and possibly a decrease in the postoperative hospital length of stay. However, this technique also has a steep learning curve, requires expensive operative equipment, and exposes the patient and surgical staff to significantly more radiation than open surgery. Furthermore, it is important that basic biomechanical principles (such as the clear superiority of bilateral compared to unilateral pedicle screws) and surgical principles (such as achieving a thorough decompression of the neurologic elements not be violated) are still followed when performing minimally invasive surgery (MIS).

89.4 Indications

Indications for percutaneous pedicle screw fixation are similar to those of open techniques:

- Spondylolysis
- Spondylolisthesis
- Instability (postlaminectomy, posttraumatic)
- Scoliosis
- Pseudarthrosis

89.5 Contraindications

The contraindications for percutaneous pedicle screw fixation are somewhat relative to the surgeon's skill; however, some universal conditions preclude this technique. Morbidly obese patients may present a problem, as the retractor tubes may not be long enough to reach the spine. Generally, if the distance from the skin to the screw insertion point is greater than 9 cm, an open technique is recommended. Posterior osteotomies and sagittal deformity correction are also better suited to open techniques. Until minimally invasive systems are improved, most spinal tumors and both column spinal injuries are typically treated using open techniques.

89.6 Special Considerations

Pedicle screw instrumentation requires detailed anatomical knowledge of the bone and soft tissue regardless if performed open or percutaneously. Because percutaneous instrumentation is performed without the familiar visual anatomical landmarks, utilization of fluoroscopic or computed tomography (CT) is necessary, and the technique should not be performed without experienced radiology technicians who can provide accurate images and minimal radiation exposure to the patient and operative team.

Lastly, while neuromonitoring is not always utilized in the placement of open pedicle screws, it is recommended for MIS pedicle screw placement.

89.7 Special Instructions, Positioning, and Anesthesia

General anesthesia is used for all patients with pedicle screw instrumentation, and must be compatible with neuromonitoring. The first step in patient positioning is placing the patient prone on a radiolucent operating table with the hips in extension to increase lumbar lordosis and prevent an iatrogenic flat-back deformity. The surgeon should take care to ensure that the patient's spine is parallel to the floor and aligned perpendicular to the fluoroscopy beam, which is generally locked at 0 degrees. However, in cases with significant rotational deformities, the fluoroscopic angle will have to be adjusted with each level. When patient positioning is correct the operative team may proceed to fluoroscopic identification. On the anteroposterior (AP) image, the end plates should appear as a single sclerotic line, and the pedicles should be clearly visible as ovals spaced equidistant from the spinous process. On the lateral image, the pedicles should overlap, and the vertebral body should be completely visible. If adequate intraoperative imaging, either fluoroscopically or with an intraoperative CT scan cannot be obtained, a minimally invasive technique is not safe and should not be performed.

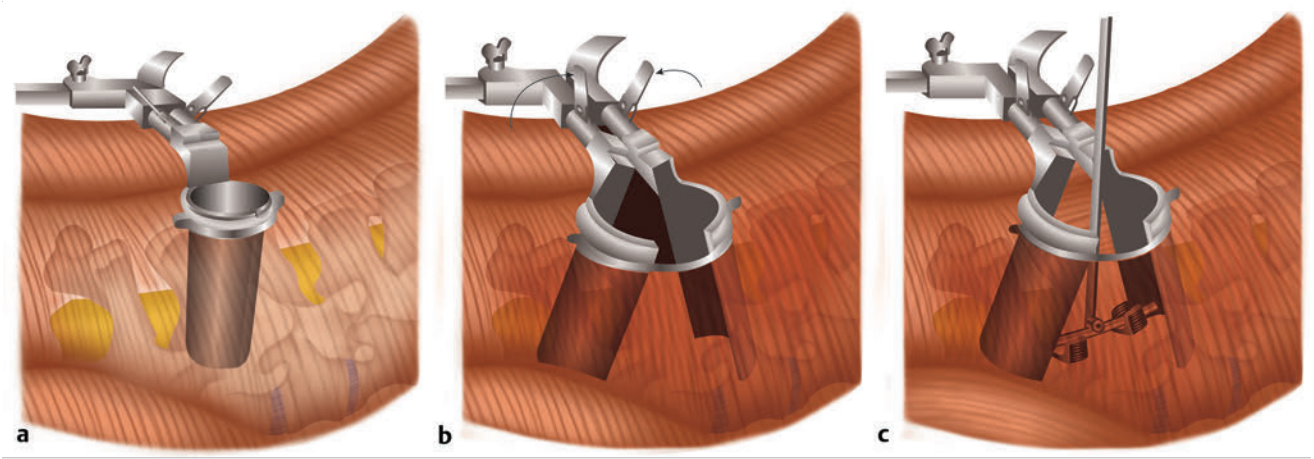

Fig. 89.1 (a–c) Example of mini-open retractor system. Shown here is the Medtronic Sofamor Danek Quadrant System.

89.8 Tips, Pearls, and Lessons Learned

Patient positioning and fluoroscopic alignment as previously described are critical to determine the starting holes and instrument orientation. The key step is ensuring the Jamshidi needle or awl is not medial to the medial wall of the pedicle (on the AP view) until it has entered the vertebral body on the lateral view. However, fluoroscopy alone is only 77% accurate in the pedicle screw placement.

The addition of electrodiagnostic modalities (nerve root monitoring, somatosensory evoked potential [SSEP], and motor evoked potential [MEP]) may increase the sensitivity of identifying misplaced screws. This can be done dynamically by electrifying wires, awls, or taps, or statically by stimulating a screw after insertion.

Computer navigation is the most accurate modality for pedicle screw placement, and it leads to less radiation exposure for the surgical team. However, the systems are expensive and increase the radiation exposure to the patient.

When placing multilevel percutaneous instrumentation, it is easier to pass the rod into the screw heads if all the screws are in the same orientation in a single plane in relation to a vertical line perpendicular to the patient's spine.

An expandable retractor or a mini-open retractor will make the procedure easier to perform (▶ Fig. 89.1).

It is important for the surgeon and the operative team to be completely familiar with the implant system they are using. Each system has its own idiosyncrasies that can lead to problems (e.g., screws can disengage from drivers or holders; blocking screws can be prematurely advanced, preventing the passing of a rod; rods can disengage from holders).

89.9 Difficulties Encountered

A medially misplaced screw is the most dangerous screw malposition because it can damage the neural elements. This is seen on the fluoroscopic imaging when the screw breaches the medial pedicle wall on the AP image prior to entering the vertebral body on the lateral image. Additionally, the surgeon is alerted to this situation by the neural monitoring. If the nerve depolarizes at a current of < 15 mA, a medial wall breach is possible, and if the nerve depolarizes at a current of < 10 mA, there may be a significant pedicle wall disruption and nerve root irritation. These thresholds may vary from institution to institution. All medial screws should be removed and redirected. Another Jamshidi needle or pedicle awl can be placed in the starting hole and directed in a more vertical orientation to redirect the screw. Alternatively, a more lateral starting hole can be made. However, neural monitoring often will remain abnormal even with an appropriately placed new screw because there is decreased electrical resistance secondary to the disruption of the medial wall.

Lateral screws should be repositioned to maintain screw pullout strength, and this situation is usually identified when the screw insertion torque feels less than normal. In addition, any wire passed through the screw may pass around the vertebra and anterior to the spine. Remove the screw, use the same starting hole, and redirect the pedicle preparation tool in a more medial direction. Then, place another screw as usual.

One of the more challenging steps in a minimally invasive fusion can be the passage of the rod through the screws. If the rod does not easily pass through the screws, there are several things that must be checked. If a locking screw has been prematurely tightened, it may not allow the rod to pass. The rod also may not pass if the screw disassembles from the screw holder; in this case the screw must be removed, reassembled, and reinserted. Lastly, in a multilevel construct, the screw extensions may not line up perfectly, and this may prevent rod passage. In this case, the screws may need to be rotated slightly and the rod holder gently tapped to advance the rod. Alternatively, the skin and fascia incisions can be extended, and the muscle tissues bluntly dissected down to the screw heads to allow for direct visualization of the rod passage.

89.10 Key Procedural Steps

A small skin incision is made between the midpoint and the lateral tip of the transverse process. This location is individualized by patient: The larger the patient, the more lateral the incision is made (▶ Fig. 89.2 a). After the incision is made, a Jamshidi

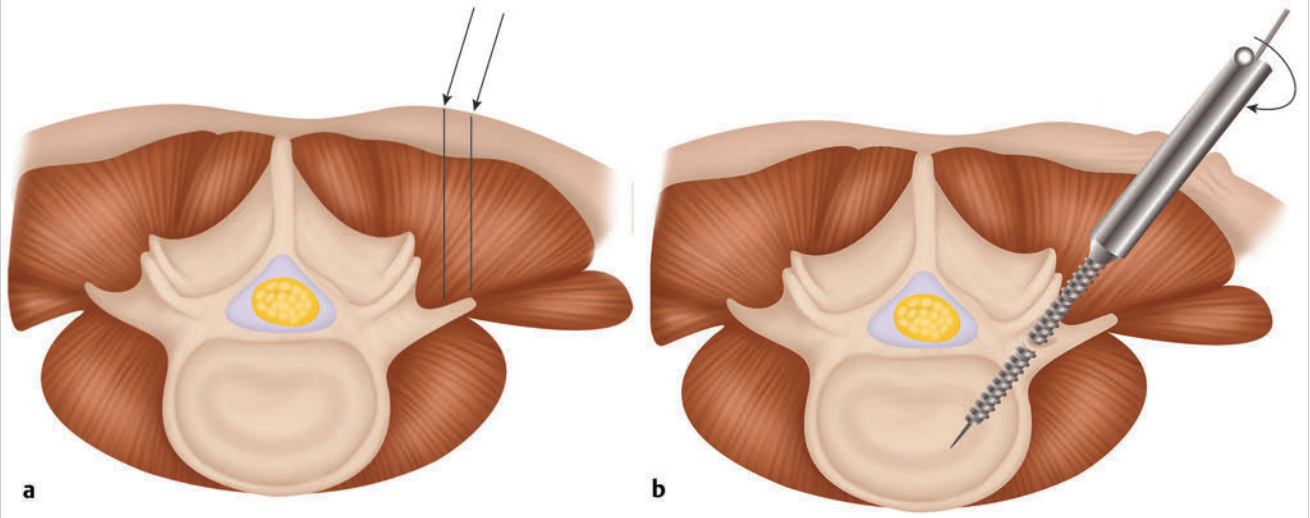

Fig. 89.2 (a, b) Determining trajectory with percutaneous pedicle screw systems.

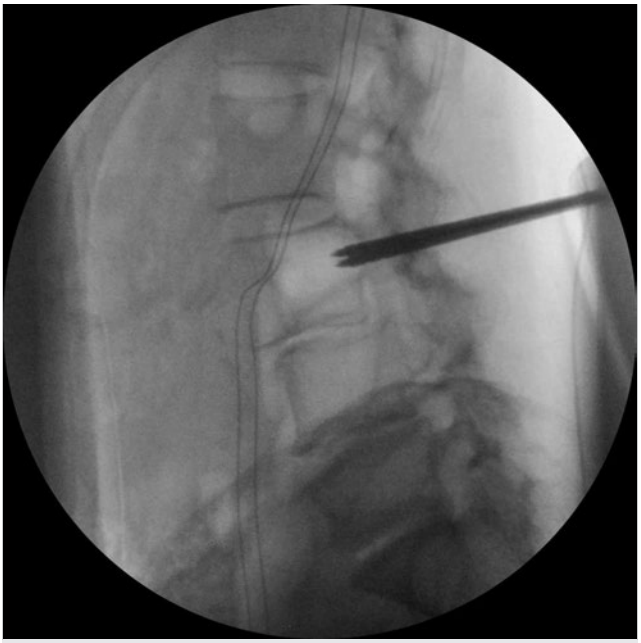

Fig. 89.3 Lateral intraoperative image demonstrating advancement of a Jamshidi needle into the vertebral body.

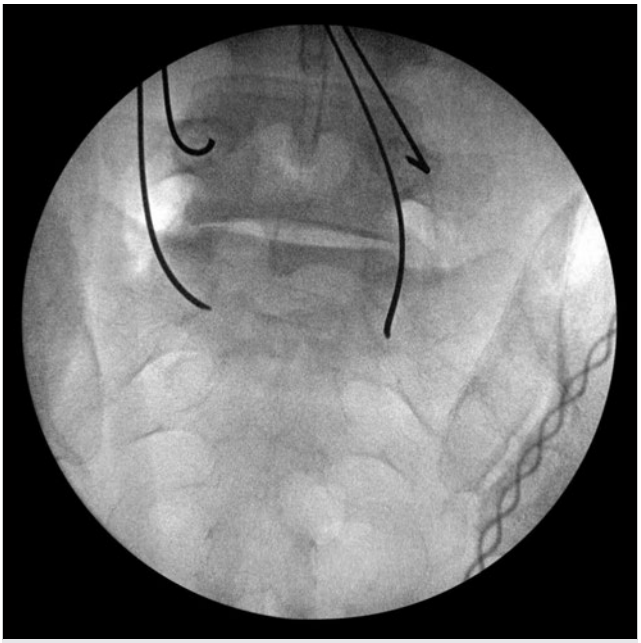

Fig. 89.4 Anteroposterior intraoperative image demonstrating placement of guidewires within the pedicles bilaterally.

needle (CareFusion) is advanced from the skin, through the fascia, and into the usual starting hole of the pedicle (for the lumbar spine, this would be the lateral border of the facet and the midpoint of the transverse process). The Jamshidi needle is advanced into the pedicle; it is critical that the needle does not breech the medial wall of the pedicle on the AP image, until it has entered the vertebral body on the lateral view (▶ Fig. 89.3). Once the Jamshidi needle is in the vertebral body, the needle can be removed, and a wire is passed through the Jamshidi trocar. The process for the contralateral pedicle is repeated in the same manner (▶ Fig. 89.4, ▶ Fig. 89.5). We prefer to place the Jamshidi needles on the same level pedicles bilaterally on the AP view prior to the lateral view to operate more quickly and use less radiation. Once the wires are in the correct position, dilators, a tap, and finally the pedicle screws can be placed (▶ Fig. 89.2 b). Once the pedicle screw is placed, neuromonitoring should be performed to verify there is not a medial breach.

Although MIS pedicle screws are traditionally placed with fluoroscopic guidance, computer navigation may increase the accuracy and decrease the amount of radiation exposure to the surgical team. However, these machines are expensive, and there is increased radiation exposure to the patient. Using this method, a reference guide is inserted into the iliac bone or on an exposed spinous process. The CT imaging equipment is then brought into the operative field, and an imaging sequence is performed. Once the images are transferred to the computer,

Fig. 89.5 Lateral intraoperative image with guidewires in place.

the navigation sequence is started. The skin incision is localized, and dilators are used to create a path to the pedicle screw starting point. Next, a navigated pedicle tap is advanced through the pedicle into the vertebral body. We prefer to prepare each pedicle prior to placing screws to prevent crowding by the pedicle screw towers. After the pedicles are prepared and the pedicle paths are saved on the computer, the screws are placed into the pedicles by matching the screw trajectory to the pedicle paths with navigation. Once the screws are in place, the rod is passed onto the screw heads and the blocking screws are placed, tightened, and counter-torqued. Prior to rod placement, another intraoperative CT image can be taken to ensure accurate screw placement, but this significantly increases the radiation exposure to the patient.

89.11 Bailout, Rescue, and Salvage Procedures

Many of these techniques have already been described; however, the surgeon must be patient and think through the problem. If for any reason a tubular or percutaneous retractor must be reinserted, it is advisable to always pass a guidewire through the instrument in the wound. In this way, the exposure will be maintained without having to redo the positioning or the fluoroscopy. Remember, the case can always be converted to an open procedure by extending the skin and fascia incisions and using blunt dissection through the muscle planes to the spine.

Pitfalls

- It is mandatory to have experience in open spinal instrumentation techniques prior to performing percutaneous techniques. Failure to thoroughly understand the anatomy of the spine and classic surgical techniques may result in significant injury to the patient.
- Misplaced screws are one of the most common and troubling complications of MIS. Medial, superior, or inferior pedicle position can be detected on fluoroscopy or by low amplitude nerve root depolarization on neural monitoring. A laterally placed screw is often detected by loss of tactile resistance with torque. A guidewire can be placed through the cannulated screw and identified anterior or lateral to the bone on fluoroscopy. If intraoperative navigation is available, CT imaging can be performed once all screws are placed, but before the rods are placed to verify screw position.
- A nerve injury can be suspected by nerve monitoring or worrisome fluoroscopic imaging. The best practice is to avoid this complication by following the techniques in this chapter. However, if an injury is suspected or if bone or metal is in proximity to the nerve, it must be removed. An open or minimally invasive canal exploration may be necessary. Postoperatively, a nerve injury or misplaced screw is confirmed by a CT/myelogram with reformatted images.
- Vascular injuries are exceedingly rare. If a screw is placed anterior or an instrument or damages a vessel, the bleeding is controlled with a hemostatic agent such as FloSeal (Baxter Healthcare) and the area or pedicle hole is packed. A vascular surgeon should be consulted immediately.

90 Anterior Thoracoscopic Deformity Correction and Instrumentation

Alex Ching

90.1 Description

This procedure provides an anterior approach to the thoracic spine without the morbidity of traditional thoracotomy.

90.2 Key Principles

Anterior release of disk spaces allows for improved deformity correction and potential improved fusion rate, while decreasing the morbidity of traditional approaches.

90.3 Expectations

Correction of the scoliotic curve and a thorough arthrodesis can be expected through the endoscopic approach.

90.4 Indications

Indications for scoliosis surgery are well described. Posterior instrumentation and fusion remains the gold standard for the surgical treatment of scoliosis. By providing better access to the disk and anterior longitudinal ligament, anterior releases allow for greater deformity correction, especially in rigid or larger-degree curves. In children with significant growth potential, anterior surgery can address the potential for the "crankshaft" phenomenon of continued anterior spinal growth around a posterior tether. Anterior interbody fusion potentially decreases the risk of pseudarthrosis. Hypokyphosis is a relative indication for anterior instrumentation, as this instrumentation is kyphogenic in nature. Structural curves isolated to the thoracic spine also are more amenable to thoracoscopic surgery than curves extending into the lumbar spine.

90.5 Contraindications

Thoracoscopic surgery requires single-lung ventilation. Any condition that precludes single-lung ventilation is a contraindication for this technique. Pleural adhesions, such as those that occur in the setting of recurrent pulmonary infections, make visualization and surgery more challenging. Small children (< 20 kg) and patients with severe scoliosis, resulting in decreased working space within the chest cavity, are also contraindicated. Finally, if the thoracoscopic surgery fails intraoperatively, the case must be converted to open. Therefore, any contraindication to open anterior thoracic surgery (such as poor preoperative pulmonary function) is also a contraindication to thoracoscopic surgery.

90.6 Special Considerations

This is an extremely technically demanding procedure. It requires specialized instruments, enough experience treating spinal deformity to know which patients are appropriate candidates, and a high degree of comfort working though the endoscope. Open, posterior spinal fusion with segmental fixation yields an identical long-term result, with better biomechanical fixation. Thoracoscopic surgery may result in better cosmesis and may save one or two levels of fusion, but is otherwise equivalent, at best, to posterior segmental fixation.

90.7 Special Instructions, Positioning, and Anesthesia

The left lateral decubitus position allows for direct access to the right thoracic spine in the setting of a right thoracic curve. The surgeon and assistant usually work from the ventral surface of the patient, looking across to the video monitors positioned behind the patient. This positioning most closely mimics the positioning for a traditional thoracotomy approach, allowing for better orientation of the surgeon in space. Single-lung ventilation with a double-lumen endotracheal tube allows for better retraction and visualization of the spine, and decreases the risk of lung injury from sharp instruments. Placing the patient tilted slightly forward allows for some retraction of the deflated lung due to gravity. The draping of the patient should be wide enough to allow for conversion to open thoracotomy, should that be necessary.

90.8 Tips, Pearls, and Lessons Learned

This is a technically demanding procedure. Contra-indications to open anterior thoracic surgery are also contra-indications to thoracoscopic fusion. Visualization can be challenging, but is assisted by single lung ventilation. Portal placement and spacing is critical to assist in visualization and disc space preparation. Adequate disc space preparation and bone grafting to achieve solid arthrodesis is critical.

90.9 Difficulties Encountered

Adequate visualization can be impaired by suboptimal hemostasis, inadequate retraction of the lung and great vessels, and inappropriate endoscope positioning.

90.10 Key Procedural Steps

Portal placement is done in a similar manner to chest tube placement, just above the lower rib to avoid the neurovascular structures located just inferior to the upper rib. After the first portal is placed, an endoscope is used to visualize the interior of the chest cavity, the deflated lung, and to look for any adhesions or other structures at risk during placement of additional

portals. Although the number and the orientation of additional portals is often dictated by the planned procedure and the anatomy of the spine, between three and five portals along the anterior axillary line is most common. Once the portals have been placed, the parietal pleura is then divided longitudinally, taking care to identify and either ligate or preserve the segmental vessels. This allows for direct exposure of the lateral vertebral bodies and the intervertebral disks. When the segmental vessels are divided and a sponge is packed in the plane between the spine, esophagus, and great vessels, a wide view of the vertebral bodies is obtained.

Disk preparation is done in a similar manner to open surgery: An anulotomy is performed, then the nucleus pulposus is removed. The cartilaginous end plate of the disk should be resected to expose bleeding cancellous bone as preparation for bony fusion. At each level, the working portal should be roughly in line with the disk space with an angled endoscope at an adjacent portal to allow for adequate visualization of the depth and orientation of the instruments. Specialized instruments designed to work through the thoracoscopic portals facilitate this portion of the case.

Bone grafting follows the standard principles of bony fusion. These include preparation of the bony end plates, appropriate graft selection (allo- vs. autograft and bone graft extenders), and aggressive packing of the disk space with graft. The decision for structural versus nonstructural graft will depend on the specific case, just as in open surgery. A long funnel-like device is often used for graft delivery through the portals.

If anterior instrumentation is going to be used, these screws are placed using a separate set of more-posterior portals, usually located just anterior to the lateral border of the scapula. The exact location of these portals is based on screw trajectory. Percutaneous guidewires are placed into the vertebral bodies in the appropriate screw trajectory, which is then confirmed on fluoroscopy. The portals are then placed where these guidewires pass through the chest wall. The screws are placed parallel to the end plates, aiming for a bicortical purchase, using an awl, tap, and ball-tip probe, and then screw placement, followed by fluoroscopic confirmation of position.

Rod placement, reduction into the screws, compression for correction of deformity, and locking cap placement is accomplished using specialized tools specific to the implant system being used.

90.11 Bailout, Rescue, and Salvage Procedures

Open posterior fusion with segmental instrumentation remains the gold standard treatment for adolescent scoliosis. This allows for a high degree of deformity correction, with a very high rate of fusion and optimal biomechanical stability.

Pitfalls

- Achieving solid arthrodesis is critical to any spine fusion procedure.
- Appropriate end plate preparation and bone grafting is more challenging endoscopically.
- Anterior spinal hardware is more technically demanding and less biomechanically rigid than posterior hardware, raising the potential for fixation failure.
- Both of these factors increase the risk of nonunion with this technique.

91 Minimally Invasive Rod-Insertion Techniques for Multilevel Posterior Thoracolumbar Fixation

Michael C. L. Suryo, Sapan D. Gandhi, and D. Greg Anderson

91.1 Description

Multilevel, minimally invasive spinal instrumentation is used for a variety of spinal pathologies, including spinal deformity, tumors, infections, trauma, and degenerative disease.

91.2 Key Principles

As with all minimally invasive spinal procedures, care should be taken with the handling of the paraspinal soft tissue envelope. Prior to beginning the procedure, imaging studies should be examined to develop a preoperative plan, which should include the goals of surgery, workflow, and equipment required to complete the procedure. Intraoperative imaging is crucial for minimally invasive spinal procedures and is typically accomplished using a C-arm fluoroscopy. Prior to making any incisions, bony landmarks should be identified and marked out. Proper alignment of the C-arm when implanting percutaneous instrumentation is critical. Only true anteroposterior (AP), true lateral, or en face views should be used during pedicle targeting. Alignment of all implants is important for rod passage and reduction of the rod and screw implants.

91.3 Expectations

Multilevel, minimally invasive procedures have the potential to preserve muscle and ligamentous structures, minimize muscle retraction, decrease blood loss, decrease postoperative pain, lower the rate of surgical site infection, and shorten the hospital stay.

91.4 Indications

Complex spinal conditions include spinal deformities, tumors, infections, trauma, and multilevel spondylolisthesis.

91.5 Contraindications

An absolute contraindication to percutaneous spinal fixation is the unavailability of intraoperative imaging or the inability to visualize the pedicle anatomy. Relative contraindications include severe osteoporosis or systemic infection. Obesity adds to the complexity of the procedure, but is not an absolute contraindication. Percutaneous screw fixation can be performed safely in the obese population.

91.6 Special Considerations

Preoperative plain film X-rays, computed tomography (CT) images, and magnetic resonance images (MRIs), along with a corresponding history and physical examination, must be used to diagnose the spinal pathology. A learning curve should be anticipated for minimally invasive spinal fixation due to the new skill set that must be developed. However, a mentorship model can be utilized to learn these procedures without compromising patient care.

91.7 Special Instruction, Positioning, and Anesthesia

General anesthesia is most commonly utilized for anesthesia. The patient is positioned prone on a radiolucent spinal frame, such as a Jackson table, with careful padding of all bony prominences. Electromyography/nerve root monitoring may be used, depending on surgeon preference.

91.8 Tips, Pearls, and Lessons Learned

Obtaining a true AP and lateral view using C-arm fluoroscopy is paramount to the success of percutaneous pedicle targeting. In a true AP view, the superior end plate appears as a single radiopaque line at each level, and the pedicles will appear symmetric and immediately caudal to the superior end plate. In addition, the spinous process will appear at an equal distance between the pedicles. In a true lateral view, the posterior cortex and anterior cortex of the vertebral body will project as a single radiopaque line, with the pedicles superimposed. To obtain the en face view for better visualization of the pedicles, begin with a properly aligned true AP view and then rotate the C-arm towards the side of the pedicle until the beam is aligned with the central axis of the pedicle.

91.9 Difficulties Encountered

Surgeons at the beginning of their learning curve may experience longer operating times. The most critical steps include proper alignment of the C-arm images, accurate targeting of the pedicles, and good alignment of the implants to facilitate rod passage. Inability to complete any of these steps would make a percutaneous approach impossible.

91.10 Key Procedural Steps

91.10.1 Approach

After the sterile prep and drape of the surgical field, bony landmarks should be identified and marked. Using the true AP view, a K-wire is placed above the skin so that it bisects the pedicles on the fluoroscopic image at the level of interest. A horizontal line is then drawn on the skin along the K-wire. This step is repeated for each level to be involved in the final construct. Next, the lateral margin of each pedicle is demarcated using a

K-wire in the true AP view and a vertical line is drawn on the skin corresponding to the lateral aspect of the right and left pedicles. Skin incisions should be positioned 10 to 15 mm lateral to the intersection of the horizontal and vertical lines, although a more lateral incision may be required in obese patients.

91.10.2 Percutaneous Pedicle Targeting

The skin and fascia are incised and a Jamshidi needle is docked at the starting point of the pedicle screw insertion for that particular level. In the lumbar spine, the Jamshidi needle is docked at the intersection of the lateral aspect of the superior articular process and the transverse process. Thoracic vertebrae typically have the same starting point for pedicle screws; however, the transverse process in the thoracic spine does not reliably match up to the pedicle and caution should be used when inserting pedicle screws. Regardless, the location of the needle tip is then evaluated using the true AP fluoroscopic view and the needle tip is adjusted as needed to localize the needle tip at the 9 o'clock pedicle position on the left and 3 o'clock position on the right. Once the needle tip is in the correct position, the needle is gently tapped to penetrate the cortex to a depth of about 2 to 3 mm (bone divot), to hold the Jamshidi in the appropriate place. The shaft of the needle is then marked 20 mm above the skin edge, to allow the surgeon to follow the depth of the needle as it passes through the pedicle. The needle is held with a slight lateral to medial trajectory and is aligned parallel to the superior end plate. The needle can then be tapped through the pedicle to the 20 mm depth and a true AP image is obtained and evaluated. The needle tip should lie within the pedicle shadow, about one-half to three-quarters of the distance (from lateral to medial) across the pedicle.

After confirming that the Jamshidi needle has successfully traversed the pedicle, a guidewire is placed through the needle and advanced about 15 to 20 mm into the cancellous bone of the vertebral body. The surgeon should be able to palpate the crunchy texture of the cancellous bone once the vertebral body has been reached. Next, the C-arm is switched to the lateral view and the pedicles are tapped (as needed) and cannulated screws are placed. These steps can be repeated for each pedicle screw to be part of the final construct. Care should be taken to align the screw depths during screw placement to facilitate rod passage. The alignment of the cannulated screws can be determined by assessing the contour of the screw extensions.

91.10.3 Rod Insertion during a Multilevel Procedure

First, rod length is measured and the rod is contoured according to the sagittal profile for the region of the spine being treated. Rod passage is most often performed with the rod attached to a rod holder and sequentially passed through each of the extensions beginning at one level of the construct. One possible rod passage strategy is for the surgeon to use the dominant hand on the rod holder, while the nondominant hand is used to manipulate each screw extension sequentially as the rod is passed. To confirm successful placement, the surgeon can attempt to rotate the screw extensions. If the rod has been successfully placed through a screw, rotation of the extension should not be possible. Once the rod has been passed through each extension in the construct, a set screw is placed at the far end of the construct (opposite the rod holder), and the rod holder is removed. The next set screw is placed at the most lordotic portion of the construct. The remaining set screws are placed with rod persuasion used as needed to facilitate reduction of the rod into each screw. Final tightening of the construct is then performed and the screw extensions are removed.

91.11 Bailout, Rescue, and Salvage Procedures

In the event that adequate visualization of the pedicle anatomy is not possible, the surgeon should be prepared to convert to an alternative, open surgical approach to insert instrumentation. In addition, adjustment of screw depth and positioning may be required in the setting of poor pedicle screw alignment or positioning.

Pitfalls

- Poor placement of pedicle screws will make rod passage difficult or even impossible.
- In addition, inability to obtain adequate visualization via fluoroscopy may lead to misplaced pedicle screws.
- Breach of the pedicle screws medially, anteriorly, cephalad, or caudally can lead to serious neurologic and vascular consequence.

92 Minimally Invasive Posterior Deformity Correction Techniques

Kelley E. Banagan and Steven C. Ludwig

92.1 Description

Performing spinal procedures in a minimally invasive fashion has become widely accepted and practiced. The benefits of minimally invasive surgery (MIS), including decreased blood loss, lower infection rates, shorter hospital stays, and less tissue destruction, have been well documented. Deformity correction surgery has classically been associated with larger, open procedures. However, minimally invasive techniques have a role in deformity correction surgery. More specifically, deformity correction techniques include minimally invasive facetectomies, lateral interbody fusions, and transforaminal interbody fusions with the addition of posterior percutaneously placed pedicle screws.

Minimally invasive surgical techniques and strategies are emerging as useful tools to augment, and in some instances surpass, traditional open strategies. The use of these techniques is expanding. However, optimal surgical technique, patient selection, and knowledge of the inherent limitations of MIS are necessary as the role of minimally invasive deformity correction emerges.

92.2 Key Principles

The principles of minimally invasive deformity correction do not differ from the principles that guide standard open approaches. Recognition of coronal and sagittal balance correction is of paramount importance, as is the appropriate proximal and distal extent of the construct. Knowledge of normal spinal anatomy is essential when performing deformity surgery, considering dysplastic, congenital, iatrogenic, and/or traumatic anatomical changes might be present. Such knowledge is increasingly critical when performing MIS because not all bony landmarks can be readily identified or visualized. Obtaining solid biological fusion can also be challenging when performing both open surgery and MIS. Long-term maintenance of curve correction and optimization of patient outcomes can be achieved in the presence of solid fusion. Patient selection remains crucial, as does the most appropriate technique to meet the surgical needs.

92.3 Expectations

The surgeon should not expect that minimally invasive techniques will completely replace the need for open deformity correction. Larger sagittal and coronal imbalances requiring correction will likely require an open procedure or at least a hybrid approach that combines open and minimally invasive techniques. The surgeon should expect a learning curve when performing minimally invasive techniques. He or she should be prepared for the potential need to convert to open surgery.

92.4 Indications

Minimally invasive deformity correction plays a role in the treatment of adult degenerative kyphoscoliotic deformity, pediatric deformity, iatrogenically induced deformity, spondylolisthesis, infectious deformity, and traumatic deformity. Intraoperative visualization is imperative when performing MIS.

Emerging techniques with computer-assisted image-guided surgical stations allow one to perform minimally invasive techniques in the absence of fluoroscopic imaging. These new techniques can be helpful when performing MIS on morbidly obese patients or when attempting to apply instrumentation to the upper thoracic spine through a minimally invasive approach.

92.5 Contraindications

Intraoperative visualization is imperative when performing MIS. Therefore, if it is not possible to visualize the appropriate anatomical landmarks with fluoroscopy, MIS might not be an option.

Minimally invasive surgery might not be the most appropriate choice for revision surgery of pseudarthroses for which greater access to bony landmarks and surfaces might be needed. It might not be the best choice for deformities requiring large corrections for which open exposure is necessary for visualization and decompression of the spinal canal and for osteotomy techniques.

92.6 Special Considerations

Surgeons should not try to perform minimally invasive techniques for spinal deformity correction until they have mastered spinal deformity correction through an open approach. The same standard principles applied to open techniques should be generalized to minimally invasive techniques. Additionally, one should also develop basic MIS skills for more straightforward indications before embarking on a case with complex thoracolumbar deformity.

92.7 Special Instructions, Positioning, and Anesthesia

When performing minimally invasive deformity correction, one must consider the pathological portion of the spine to be addressed, the levels to be corrected, and the levels to receive instrumentation when planning the surgical approach and position of the patient. The patient typically is positioned prone on a radiolucent table. These procedures are almost exclusively performed with the patient under general anesthesia.

92.8 Tips, Pearls, and Lessons Learned

- Consider minimally invasive deformity correction for patients with degenerative scoliosis and coronal deformity. Lateral interbody fusion techniques are useful for correcting coronal imbalance.
- Facet fusion is an excellent option for obtaining fusion in the setting of pedicle screws placed in a minimally invasive fashion.
- If the surgeon does not have the experience and the necessary equipment for MIS, MIS should not be attempted.
- Knowledge of spinal anatomy is crucial.
- Applying instrumentation to the upper thoracic spine in a minimally invasive fashion can be extremely difficult because of poor fluoroscopic visualization.
- Intraoperative visualization in a morbidly obese patient is challenging and might preclude performing MIS.
- Standard open procedure techniques should always be considered.

92.9 Difficulties Encountered

Obtaining fusion in a compromised host can be difficult regardless of the approach chosen. Optimization of the patient before the planned procedure is essential. However, even then, the fusion bed might not be sufficient or sufficiently visualized. For instance, in cases in which substantial facet arthropathy or overgrowth is present, facet fusion through a tubular retractor might not be possible. In this instance, interbody fusion through a lateral approach or an anterior approach with MIS placed screws can be a better option. If visualization with intraoperative fluoroscopy proves difficult, open surgical techniques can be performed, or if available, computer-assisted navigation might be an acceptable and useful bailout plan.

92.10 Key Procedural Steps

The procedure starts with patient selection. Minimally invasive surgical techniques cannot be used for every patient. The most crucial "procedural" step is identifying the patient for whom a minimally invasive approach can be used. Considerations include the patient's body habitus and bone quality, the nature of the deformity, and the number of previous surgical procedures the patient has undergone. Once a patient has been deemed a candidate for MIS, patient positioning becomes crucial. The patient must be positioned in such a way to accommodate intraoperative fluoroscopy so adequate visualization of the vertebral body and pedicles can be achieved. As noted above, instrumentation in the upper thoracic spine can be difficult; the surgeon should therefore be prepared to convert to an open procedure.

For deformity correction surgery, preoperative planning is the most essential procedural step. The goals of the surgery—correction of a sagittal-plane deformity or a coronal-plane deformity or both—should be clearly delineated, and the surgical means to accomplish the correction should be determined. As noted above, a hybrid approach might be necessary if an osteotomy is to be performed because accomplishing a large correction through a minimally invasive approach might not be feasible. Identifying the relevant anatomy and assessing the rigidity of the spine are helpful in determining whether a solely MIS approach is possible. As with open procedures, a key step in minimally invasive deformity correction is rod contouring. In the setting of sagittal plane correction, it is helpful to undercontour the rod.

At the levels to receive instrumentation, pedicle screws are inserted in the standard fashion with intraoperative anteroposterior (AP) targeting for the start points. Once the screws have been placed and confirmation of appropriate placement has been obtained with AP and lateral view fluoroscopy, a rod is cut, contoured, and passed in a subfascial plane.

In the trauma setting, many deformities are kyphotic and might or might not have an associated translational deformity or component. In traumatic deformity cases, it is helpful to undercontour the rod. Once the rod is passed, the spine can then essentially be reduced to the rod. This usually is accomplished by attaching the necessary reduction devices to the screw extensions. Initially, the rod typically is locked distally. A cantilever reduction maneuver is then applied via the screw–rod interface to translate the proximal portion of the deformity.

If the spine fails to reduce or if fusion is deemed essential, the facets can be visualized through a minimally invasive approach. A tubular retractor is placed over the facets, and the overlying soft tissues are cleared with Bovie electrocautery. Once the facets are visualized, a high-speed bur is used to decorticate the facets. Taking down the facets will help to facilitate reduction of a dislocated and/or translated spine in addition to performing a corrective maneuver. Tubular exposure of the facet joint also allows for the creation of a fusion bed. Graft material can then be introduced via the retractor and packed over the decorticated facet joints.

In correction of degenerative lumbar scoliotic deformity, interbody devices placed through a minimally invasive transforaminal approach or via a lateral approach allow for direct or indirect decompression of the neural elements and the delivery of the appropriate biological agent with simultaneous correction of the spinal deformity. The upper lumbar segments are best suited for a lateral approach. The patient is positioned in a lateral position and the spine accessed through a retroperitoneal approach. This can be accomplished with tubular retractors or a mini-open approach with radiolucent retractors. The psoas muscle is retracted posteriorly or divided in the anterior third to avoid neurovascular structures. Neuromonitoring is recommended.

The disk space is identified, diskectomy is performed, and a structural graft or cage is placed. This typically is performed on the concavity of the spine, which helps to address the coronal imbalance and a component of the sagittal imbalance associated with the deformity. The patient can then be transitioned to a prone position with pedicle screws inserted through a minimally invasive approach with further correction of the spinal deformity. In the lower lumbar segments, where the lateral approach might be a more challenging option, minimally invasive transforaminal interbody fusion can be performed. Moreover, when faced with a patient requiring fusion crossing the thoracolumbar junction to the sacrum, iliac screws to aid in maintaining the correction and assist in achieving stability across the lumbosacral junction are added to prevent the

potential for pseudarthrosis. Percutaneously positioned iliac screws can be placed through a centralized incision.

When faced with a patient with substantial coronal and/or sagittal imbalance requiring an osteotomy procedure, implementing a hybrid technique—a portion of the procedure is performed in the standard open fashion and a portion is performed in a minimally invasive fashion—can achieve all the surgical goals while simultaneously reducing some of the morbidity associated with a large open approach. Thus, performing the osteotomy through the standard open approach by limiting the surgical working zone to the specific osteotomy level can obviate the collateral damage and associated risks involved with the standard larger completely open surgical approaches. After the targeted site osteotomy has been performed, applying minimally invasive techniques through a variety of the above-mentioned approaches can complete the procedure and achieve the surgical goals.

92.11 Bailout, Rescue, and Salvage Procedures

The salvage procedure for any MIS technique is converting to an open approach. In most instances, obtaining greater visualization of the anatomical landmarks and a wider scope of dissection allows for recognition of known and normal landmarks, and by default provides the option of performing a standard fusion-type procedure. In some instances, this can prove difficult depending on the initial incision. Therefore, it is our recommendation that the surgeon always be mindful that an open procedure might be the necessary "bailout."

Pitfalls

- Improper patient selection
- Inadequate visualization of the pertinent anatomy
- Inability of minimally invasive surgical techniques to accomplish the surgical goals (e.g., need for larger field of visualization or need for larger osteotomy, such as vertebral column resection)
- Inexperience of the surgeon in using the approaches
- Revision surgery and the inherent difficulties with scarring and distorted anatomy

93 Endoscopic Thoracic Decompression, Graft Placement, and Instrumentation Techniques

Max C. Lee, Kyle D. Fox, and Daniel H. Kim

93.1 Description

Thoracic decompressions include diskectomies and corpectomies with intervertebral grafting utilizing an interbody spacer or bone graft and anterior instrumentation, as well as thoracoscopic decompression and stabilization in the setting of trauma to the thoracolumbar junction.

93.2 Key Principles

- Thoracoscopic approach can treat T4–T10 injuries as well as thoracolumbar injuries.
- Significant cardiopulmonary disease needs to be ruled out for preoperative clearance.
- Begin portal placement with most cranial portal via mini-thoracotomy approach.
- Diaphragmatic gap with incision less than 4 cm may close spontaneously; incisions greater than 4 cm should be closed with endoscopic suturing or hernia stapler.

93.3 Expectations

The goals of operative treatment include (1) adequate decompression of the spinal canal to provide the maximum chance of neurologic recovery, (2) correction of the spinal deformity and restoration of anatomical alignment to prevent delayed spinal deformity and neurologic deficits, and (3) immediate rigid fixation for early mobilization and rehabilitation with fixation of the least number of motion segments. The approach and instrumentation selected should be able to achieve all these goals with minimal trauma to the patient.

93.4 Indications

Indications include amenable thoracic fractures involving the T4–T10 vertebrae and injuries involving the thoracolumbar junction. As many of these patients have multiple injuries, all major injuries are stabilized before the spinal procedure is done.

93.5 Contraindications

Thoracoscopic procedures are contraindicated in patients with previous cardiopulmonary disease with restricted cardiopulmonary function, acute posttraumatic lung failure, severe pleural adhesions, and severe medical instability. Routine bowel preparation is required to reduce intra-abdominal pressure and facilitate the retraction of the diaphragm. A detailed informed consent is obtained after explaining the various risks involved in the procedure, such as visceral injury, vascular injury, blood loss, instrumentation failure, failed fusion, and possible conversion to open procedure.

93.6 Special Considerations

The thoracoscopic transdiaphragmatic approach presents several unique challenges to spine surgeons that necessitate a clear understanding of the diaphragmatic, thoracic, and retroperitoneal anatomy. The entire thoracolumbar junction can be exposed thoracoscopically with minimal diaphragmatic detachment. This is made possible by an anatomical peculiarity of the pleural cavity and the diaphragmatic insertion, the lowest point of which, the costodiaphragmatic recess, is projected onto the spine perpendicularly just above the base plate of the second lumbar vertebrae.

93.7 Special Instructions, Positioning, and Anesthesia

With the patient in a supine position, double-lumen endotracheal intubation is performed. A Foley catheter, central venous line, and arterial line for continuous blood-pressure monitoring are inserted.

The patient is placed in a stable lateral decubitus position. The top-lying arm is placed flat on an arm support and raised to 90 degrees of elevation to avoid a collision during placement and manipulation of the endoscope. Sterile draping extends from the middle of the sternum anteriorly to the spinous processes posteriorly as well as from the axilla down to approximately 8 cm caudal to the iliac crest. Monitors are placed at both lower ends of the operating table on opposite sides to enable free vision for the surgeon and the assistant. The surgeon and the assistant holding the camera stand behind the patient. The C-arm monitor and the second assistant are placed on the opposite side.

93.8 Tips, Pearls, and Lessons Learned

To avoid inadvertent injury to the lungs, the diaphragm, and the organs beneath the diaphragm, the most cranial portal is inserted first via a mini-thoracotomy approach. Through a 1.5-cm skin incision placed above the intercostal space, the muscle layers of thoracic wall are cut through in a zigzag fashion following the direction of the fibers. The 30-degree scope is introduced through the portal, and the remaining trocars are inserted under direct thoracoscopic vision. The endoscopic image is rotated to obtain an orientation of the spine parallel to the lower edge of the video monitor screen. The cephalocaudal axis of the camera is oriented to the view of the primary operative surgeon to allow for normal translation of his or her hand movements to the monitor (▶ Fig. 93.1).

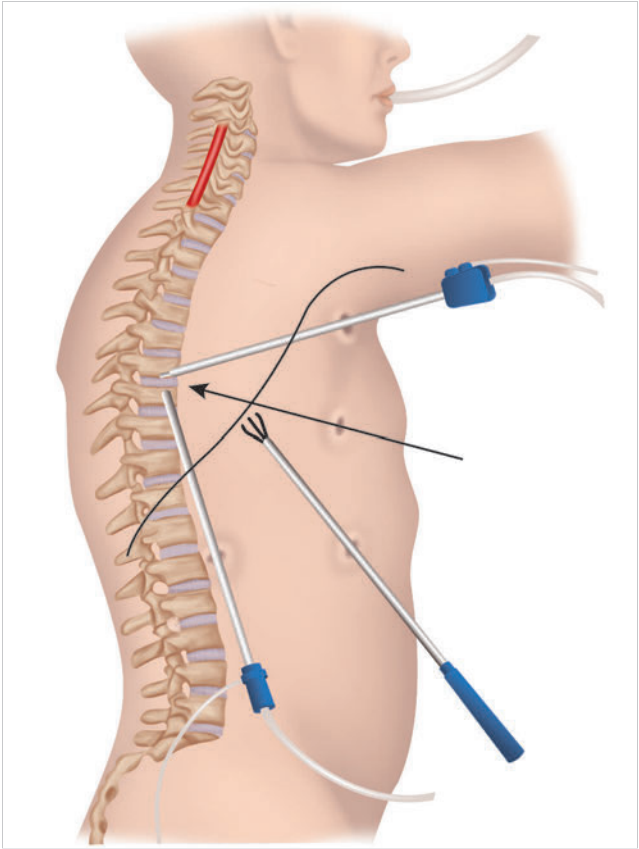

Fig. 93.1 Orientation using a three- or four-portal approach.

93.9 Difficulties Encountered

When operating in the lower thoracic region and the thoracolumbar junction, it is important to keep in mind the artery of Adamkiewicz. This is most commonly located on the left side. Injury to this artery can result in a watershed infarct of the spinal cord. A pneumothorax also can be encountered, in which a chest tube may need to be placed.

93.10 Key Procedural Steps

Under direct fluoroscopic guidance, the target fractured vertebra is projected onto the skin level. The borders of the fractured vertebra are marked on the skin. The working channel (10 mm) is centered over the target vertebrae. These steps are well demonstrated in **Video 93.1**. The optical channel (10 mm) is placed two or three intercostal spaces cranial to the target vertebra. The approach for suction/irrigation (5 mm) and retractor (10 mm) is placed approximately 5 to 10 cm anterior to the working and optical channel.

The fractured area is now exposed with the help of a fan retractor inserted through the anterior port. The fan retractor performs the dual function of holding down the diaphragm and exposing the insertion of the diaphragm on the spine. Exposure of the spine below L1 usually requires detachment of the diaphragm. Then the extent of the planned corpectomy is defined with an osteotome. The disk spaces are opened to define the borders. Trauma can obscure normal anatomical landmarks. After resection of the intervertebral disks, the fragmented parts of the vertebra are removed carefully with rongeurs. Resection close to the spinal canal is facilitated with the use of high-speed burs. If decompression of the spinal canal is necessary, the lower border of the pedicle should first be identified with a blunt hook. The base of the pedicle is then resected in a cranial direction with a Kerrison rongeur, and the thecal sac is identified. Finally, the posterior fragments, which occupy the spinal canal, are removed.

The preparation of the graft bed is completed by aggressive preparation of the adjacent end plates and complete removal of all soft tissue. The length and depth of the bone graft/spacer required is measured with a caliper. Distractible titanium cages may also be used. The graft or cage is mounted on the graft holder and inserted through the working portal incision. Longer bone grafts (> 2 cm) are inserted along their long axis through the opening and then mounted onto the graft holder inside the thoracic cavity. It is best to place the graft/cage under distraction. With the distractible titanium cages, additional reduction can be achieved by further increasing the height of the cage within the graft site.

Insert a self-tapping screw under fluoroscopic control in the vertebra superior to the fractured one, as well as in the fractured vertebra. Next, insert the first screw into the caudal vertebral body. Afterward, place the polyaxial, posterior screw over a Kirschner wire (K-wire). The stabilization plate is placed over the centralizer onto the polyaxial heads. In cases of multisegmental assemblies, rod connection has to be chosen. After the plate or rod is placed and the polyaxial plate is well aligned, the assembly can be closed by using a fixation nut. For final fixation, the torque wrench is applied to the nut driver, and countertorque is again applied by using the handle on the insertion sleeve. Remove the centralizer from the polyaxial clamp. Next, the assembly must be brought into final position directly onto the surface of the vertebral bodies. The screw-guiding sleeve for the anterior stabilization screw has to be attached to the polyaxial clamp. After selecting the appropriate screw length, fix the anterior screw to the screwdriver with a retaining clip, and then insert it through the guiding instrument into the vertebral body. Then, lock the polyaxial mechanism.

The gap in the diaphragm is closed with endoscopic suturing or hernia stapler. Smaller incisions, less than 4 cm, close by themselves without any approximating sutures. During diaphragmatic repair, care must be taken to avoid needle puncture of the lung, which may result in a bronchopleural fistula. The thoracic cavity is irrigated, and blood clots are removed. A chest tube is inserted with the end placed in the costodiaphragmatic recess. The portals are closed with sutures or staples after removal of the trocars (▶ Fig. 93.2, ▶ Fig. 93.3, ▶ Fig. 93.4).

93.11 Bailout, Rescue, and Salvage Procedures

Bailout and rescue strategies involve the conversion to an open procedure. The need for conversion may be attributed to profuse bleeding from the cancellous bone, which may be difficult to control endoscopically. Other causes include technical difficulties in the placement of implants and vascular injury. Of course, other mechanisms for decompression and stabilization may be accomplished through a posterior approach.

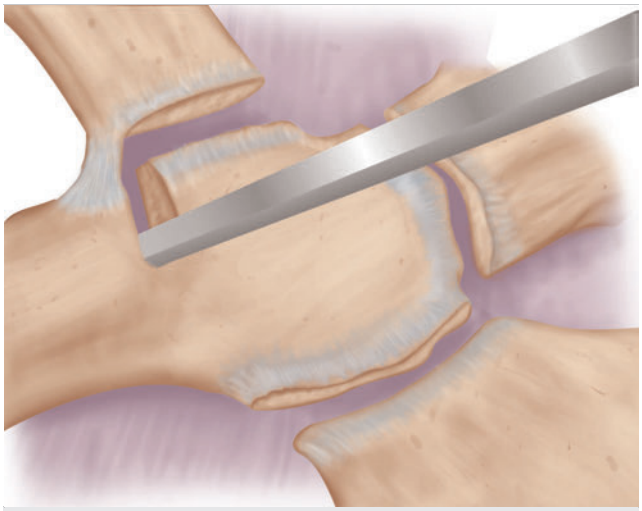

Fig. 93.2 The rib head and medial 3 cm of rib are resected with a Kerrison rongeur.

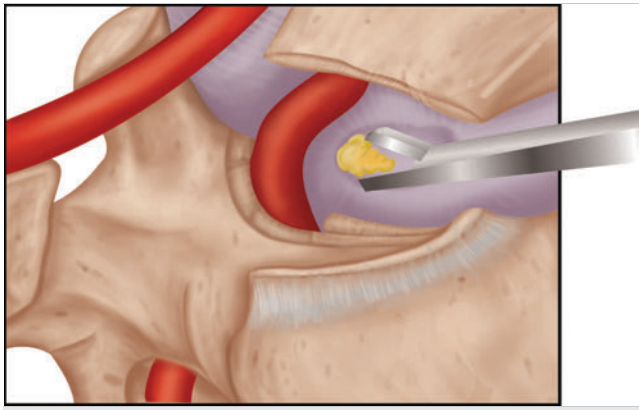

Fig. 93.4 Disk excision is performed with pituitary rongeurs.

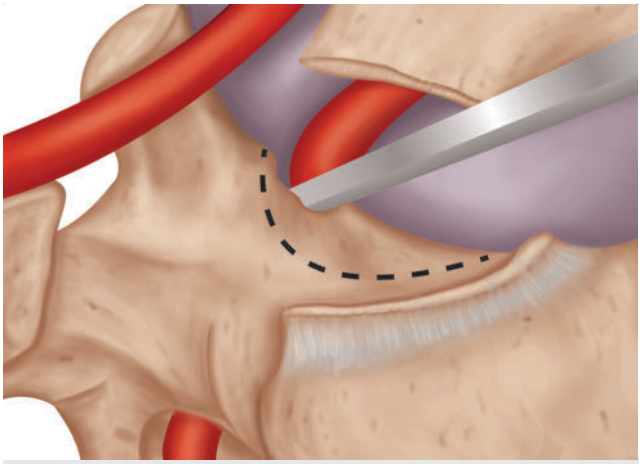

Fig. 93.3 The superior half of the pedicle is resected with a Kerrison rongeur.

Pitfalls

- Disadvantages of thoracoscopic procedures include the need for slightly increased anesthesia monitoring and preparation due to the use of double-lumen ventilation, and the fact that the procedures require considerable training and practice to master. Because the endoscopic image is two-dimensional, a certain degree of difficulty may be encountered in obtaining adequate visual orientation during the initial experience. Further, as the thoracoscopic technique requires working through smaller portals at longer distances from the target area, it requires acquisition of new cognitive, psychomotor, and technical skills to master the technique. Although difficult and challenging, the skills can be mastered with experience, and eventually operating times become shorter than for the open thoracotomy procedures.
- Various complications include implant loosening and conversion from thoracoscopic to an open surgery.
- Other complications related to endoscopic access include pleural effusion, pneumothorax, and intercostal neuralgia.
- Neurologic complications include motor and sensory deficits.

94 Minimally Invasive Sacroiliac Fusion

Alexandra Schwartz, Gregory D. Schroeder, Alexander R. Vaccaro, and Steven R. Garfin

94.1 Description

To diagnose sacroiliac (SI) joint dysfunction, one must think about it and include it in the differential diagnosis for low back pain. The SI joint is a pain generator in 15 to 25% of chronic axial low back pain patients. Once diagnosed and conservative management fails, the patient may be a candidate for SI joint fusion. Newer minimally invasive methods allow for shorter hospital stay, shorter operating time, as well as greater improvement in patient outcome and satisfaction measurements than open procedures.

94.2 Key Principles

Minimally invasive SI joint fusion is an alternative option to traditional open chondral debridement and joint fusion (using any of the described open techniques) with bone graft and internal fixation. There are numerous complications reported for open approaches, including injury to the erector spinae muscle insertions, injury to the dorsal sensory nerve roots, sacral plexus, and internal iliac vessels, non-unions, infections, and increased pain, to list a few.

94.3 Expectations

The use of a minimally invasive technique using triangular porous-coated implants driven from lateral to medial across the ilium into the sacrum has demonstrated, in retrospective and prospective studies, improved pain scores and quality-of-life measurements in the vast majority of patients; 85% of patients surveyed would undergo the procedure again.

Most report good-to-excellent relief of their SI joint-related pain, and limited complications have been observed. These including postoperative hematoma, infection, L5 nerve root irritation, and persistent pain. Computed tomography (CT) scans and radiographs demonstrate more than 85% radiographic evidence of bone on-growth to the implant and/or across the joint. Lucency (or a "halo") along the implant is seen in some patients, although the clinical significance of this finding is not clear, as excellent pain relief has been reported even with this finding.

94.4 Indications

The patient should point to the SI joint as the primary pain location and complain of pain below the iliac crests, occasionally into the buttock or proximal thigh. The exam should include neurologic and hip joint evaluations, with both of these negative, and at least 3 to 5 SI joint stress maneuvers reproducing the pain. This should be followed by intra-articular SI joint injection(s) under fluoroscopy using anesthetics with varying half-life durations to assess pain relief. The results are positive if the patient receives at least 50 to 75% pain relief/improvement in two successive injections, or greater than 75% in one injection, with a response appropriate to the duration effect of the agent used. It should be made clear to the patient that this injection is diagnostic and not therapeutic. Imaging studies (radiographs, CT scans, and magnetic resonance images [MRIs]) should be obtained to rule out other pathology, as these tests are often unremarkable in SI joint pathology. Once the SI joint is identified as a possible contributor to the pain nonoperative treatment is utilized. This includes medical management, physical therapy, injections (steroids), and maybe a pelvic belt. Radiofrequency ablation is a treatment consideration, usually performed if intra-articular injections do not give long-lasting relief. If these treatment modalities are unsuccessful and the patient has persistent disabling symptoms, the patient may be considered for sacroiliac joint fusion.

94.5 Contraindications

Contraindications to MIS SI joint fusion include deformities or anatomical variations that prevent appropriate imaging and/ or placement of the implant, a tumor of the sacrum or ilium, active infection at the SI joint or surrounding tissues, an unstable fracture of the sacrum or ilium, an allergy to metal components, and/or significant osteoporosis.

94.6 Special Considerations

Prior to any invasive procedure of the sacroiliac joint, the surgeon must have a thorough and detailed understanding of the pelvic anatomy. Appropriate high-quality images must be obtained and studied preoperatively. These usually include pelvic anteroposterior (AP), inlet and outlet views, and a CT scan. Images should be assessed, with particular attention paid to the possibility of a dysmorphic sacrum. Miller and Rout identified the following seven radiographic findings consistent with sacral dysmorphism:

1. The sacrum is not recessed within the pelvis on the outlet image. The dysmorphic upper sacrum at the level of the lumbosacral disk is colinear with the cranial aspects of the iliac crests.
2. Mammillary processes are seen on the outlet image.
3. The upper sacral foramen is dysmorphic on the outlet image. They appear larger, noncircular, misshapen, and irregular.
4. The alar slope of the dysplastic sacrum is more acute than the nondysmorphic sacrum on the lateral view. This allows for less bone available for safe implant placement.
5. A residual disk space between the upper two sacral segments is seen on the outlet image due to unusual fusion patterns during development.
6. The pelvic inlet view reveals an anterior cortical indentation, decreasing the safe zone for placement of the implant.

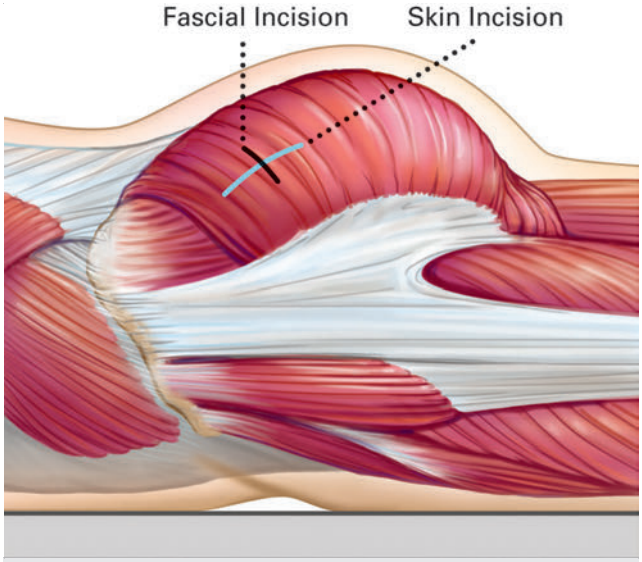

Fig. 94.1 Schematic representation of the incision for the minimally invasive sacroiliac fusion.

94.7 Special Instructions, Positioning, and Anesthesia

Minimally invasive sacroiliac fusion is done with the patient in the prone position on a radiolucent table. Rolls are placed under the patient's chest and iliac crests, and care is taken to pad all bony prominences. The arms are placed in an abducted/externally rotated position rather than adducted at the patient's side to allow for lateral fluoroscopic imaging. Biplanar C-arms may be used. If two C-arms are used, one C-arm is used in the AP and one in the lateral plane. If one C-arm is used, it is helpful to mark both the position of the C-arm machine on the floor, as well as the various angles on the "C" of the C-arm with tape. This allows for translating the C-arm proximally and distally for the inlet and outlet views, using the tape on the floor for proper location, and changing angles for the inlet and outlet views. It is also helpful to have the height of the table set high enough to allow for a good lateral sacral view, as changing the height of the table during the case may change the predetermined angles for the inlet and outlet views. Sequential compression devices are placed on both lower extremities, preoperative prophylactic antibiotics are administered, and a time-out is performed to confirm appropriate patient, position, side, implants, etc. The ability to obtain proper imaging views must be ensured prior to initiation of the surgery. When a single C-arm is used, it is positioned on the opposite side of the surgical site. If using two C-arms, the C-arm on the opposite side is most conveniently positioned to obtain the inlet and outlet AP directed views.

The inlet view is deemed ideal when all sacral bodies are overlapped, and the ideal outlet view has the S2 foramen immediately cephalad and adjacent to the superior aspect of the superior rami. The C-arm is then brought to a position to view the sacrum in the lateral view, or a second C-arm is brought into position from the same side as the surgical site to achieve the lateral view. The perfect sacral lateral view has the greater sciatic notches perfectly overlapped. The sacral lateral view is critical to understanding the sacral alar slope. The alar slope is best estimated by the iliac cortical density (ICD) and delineates the anterior extent of the "safe zone" with the implant posterior and caudal to it.

Care must be taken in patients with a dysmorphic sacrum. In these patients, the sacral alar cortical bone limit is not represented by the iliac cortical density due to the more acute slope of the sacral ala. The sacral alar cortical line is cephalad and anterior to the ICD.

The affected gluteal region is prepped and draped in the usual sterile fashion. Using the sacral lateral view for establishing the appropriate landmarks, the incision is made beginning lateral to the S1 superior end plate and extending distally approximately 3 cm in line with the posterior cortex of the sacral body (▶ Fig. 94.1). Blunt tissue dissection, opening the fascia and muscle in line with the fibers, is carried down to the outer table of the ilium.

Percutaneous techniques involve sequential placement of cannulated wires and broaches, and ultimately implantation of triangular titanium coated implants without debriding the chondral surfaces. The goal of the latter is to create stability by biological fixation of the bone to the implant with eventual bone growth across the SI joint in some cases.

94.8 Tips, Pearls, and Lessons Learned

Patients are traditionally kept partial weight bearing with normal foot progression postoperatively for 3 to 6 weeks. However, some surgeons encourage patients to progressively weight bear as tolerated.

Even though there is a relatively low morbidity from the percutaneous SI fusion/stabilization procedure itself, bilateral surgeries done under the same hospitalization are not recommended or practical due to the restrictions with postoperative mobility. In patients with bilateral symptoms, one should consider performing the procedure on the more symptomatic side first, allowing the patient to recover from the first procedure before stabilization of the contralateral SI joint. Some patients report considerable improvement of the contralateral, nonoperative SI joint after unilateral fusion/stabilization.

94.9 Difficulties Encountered

The main difficulties encountered involve the inability to achieve proper intraoperative images. Prior to prepping the patient, preliminary fluoroscopic images should be obtained to ensure adequate visualization on AP, inlet, outlet, and sacral lateral views. The radiologic technician should be familiar with the images needed. Additionally, in small people it may not be feasible to insert more than two implants, which may not be mechanically favorable, but can be done.

94.10 Key Procedural Steps

For a cannulated system, typically two to four implants (preferably more than two) are inserted. The first cannulated guidewire placed should be the most cephalad wire. The goal is to

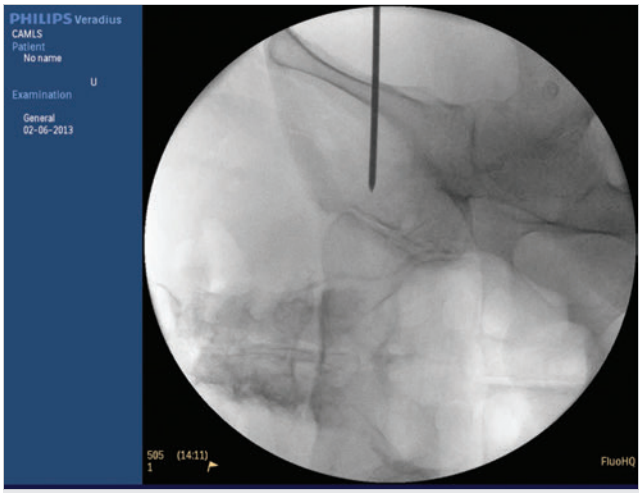

Fig. 94.2 Pin placement on an outlet view.

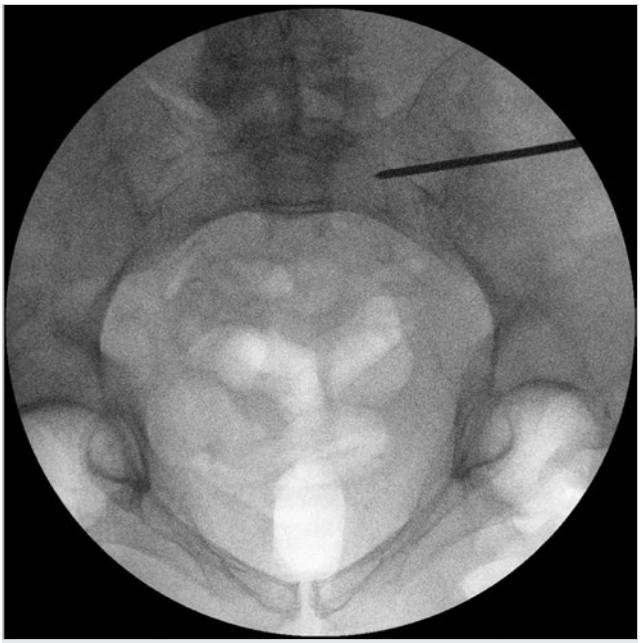

Fig. 94.3 Pin placement on an inlet view.

Fig. 94.4 Pin placement on a lateral view.

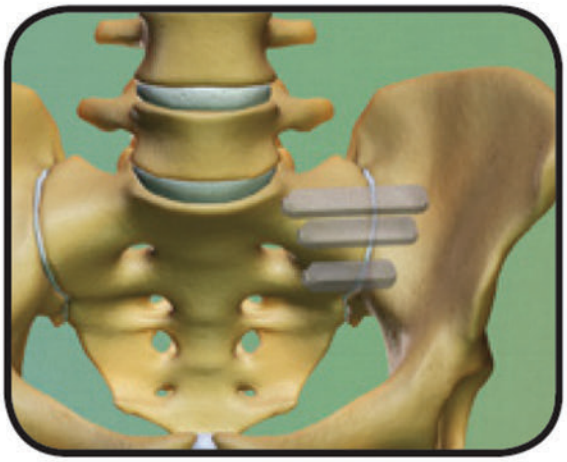

Fig. 94.5 An anteroposterior view of the pelvis showing a minimally invasive sacroiliac fusion.

center the guide pin between the S1 foramen and superior end plate of the sacrum on the outlet view, whereas maintaining the guide pin parallel to the superior end plate of S1 (▶ Fig. 94.2). On the inlet view, the guide pin should be aimed from slightly posterior to anterior, with care being taken not to violate the sacral canal or exit the front of the sacrum (▶ Fig. 94.3). To avoid the L5 nerve root, which drapes across the anterior sacrum just medial to the sacroiliac joint, the guide pin should be distal to the iliac cortical density. The pin should be parallel to the S1 end plate aiming from posterior to anterior on the lateral view (▶ Fig. 94.4). Sequential drilling, broaching, measuring, and ultimately placement of the implant then ensues. The two more caudal implants are placed with similar techniques, each ending lateral to the foramen (▶ Fig. 94.5).

94.11 Bailout, Rescue, and Salvage Procedures

If pain persists or returns after MIS fusion, the patient should have a new workup for the source of pain. Computed tomography (CT) scans should be obtained to assess the location of the implants and any evidence of healing. Diagnostic SI joint injection can assist in determining if the SI joint is the pain generator, though this may be technically challenging with the instrumentation in place. As lumbar spine pain can co-exist with or confuse sacroiliac pain, the patient should also have a thorough lumbar spine examination and radiographic workup. If the SI joint is found to be the persistent source of pain, an

open sacroiliac fusion through a direct posterior approach may be considered, but the implant may have to be removed laterally with chisels and other tools. Additionally, a "hybrid" operation involving the addition of bone graft to the existing instrumentation has been described.

Pitfalls

- Poor patient selection
- Inadequate understanding of preoperative imaging and anatomy
- Working through poor-quality intraoperative images
- Neurologic injury during placement of instrumentation
- Malposition of implants
  - Leaving implants too proud
  - Placement of implants that are too short and do not adequately engage the sacrum
  - Placement of implants that violate a neuroforamen or the spinal canal
  - Placement of implants that violate the osseous envelope of the sacrum superiorly through the ala, ventrally through the anterior sacral cortex, or inferiorly into the notch

Section XVII

Tumor Management

95 Spinal Radiosurgery for Metastases *356*

96 Surgical Removal of Intradural Spinal Cord Tumors *358*

XVII

95 Spinal Radiosurgery for Metastases

George M. Ghobrial, Mark E. Oppenlander, and Srinivas Prasad

95.1 Description

Spinal radiation has evolved into the delivery of highly focused radiation typically in a single session with minimal exposure to radiosensitive tissues. Stereotactic radiosurgery has seen an increased role in the treatment of spinal metastases, especially as an option for palliation in diffuse metastatic disease, as well as adjunctive treatment following surgery for metastatic epidural spinal cord compression. The increasing relevance of this treatment is illustrated in the growing number of patients seeking treatment for advanced stages of cancer, as it is estimated that 40% of these patients will develop spinal metastasis and 20% of this group will develop cord compression.

95.2 Key Principles

Advances in spinal radiosurgery stem from technologic advancements in the safe delivery of conformal radiation volumes, which are those that match the three-dimensional shape of the tumor. The typical radiation dose in spinal radiosurgery is given in a single session. The division into several smaller daily doses, however, has seen recent use and is termed hypofractionation. The convergence of several radiation beams concentrates the radiation dose onto the tumor, sparing adjacent tissue. Magnetic resonance and computed tomography (CT) imaging may be used for planning to define the three-dimensional space for radiosurgery calculations. A dose gradient is considered to be favorable when the radiation exposure to surrounding healthy tissue decreases considerably at the tissue–tumor interface. Limiting dose to the spinal cord, the radiosensitive structure at greatest risk during spinal radiosurgery, relies on three factors: tumor volume, treatment planning quality, and the dose applied.

Various methods exist for the application of a consistent and accurate radiation dose, varying by manufacturer. The variability between machines is seen in the form of numerous linear accelerators, differing modes for shaping each radiation beam—a technique termed collimation, and patient positioning/repositioning. Collimators produce a circular beam, whose diameter can be adjusted with an iris. Highly conformal doses can also be delivered with multileaf collimators, which provide irregular beam shapes tailored to the tumor geometry.

95.3 Expectations

Appropriate patient expectations begin during informed consent. A realistic understanding of the goals of radiosurgery must be detailed in the initial patient encounter. For example, bone metastasis is common in lung cancer, and the prognosis is a dismal 6 months median survival time, with less than a 5% 5-year survival. Patients should develop an understanding that with multiple metastases, spinal radiosurgery can be dependable as a palliative measure, with reports of pain control reaching 85 to 96% with a maximum dose of 22 Gy in a single fraction.

95.4 Indications

The generally accepted indications for radiation are palliation, treatment of metastatic disease in those with medical comorbidities that preclude surgical treatment, halting neurologic compromise, prevention of pathologic fractures, and the primary treatment of radiosensitive tumors such as multiple myeloma and lymphoma.

95.5 Contraindications

Radiosurgical planning for tumors larger than 50 cm^3 often results in a dose gradient that is not steep enough to avoid the neighboring spinal cord. Depending on overall tumor burden, palliative radiation to larger lesions is left to the discretion of the surgeon and patient.

95.6 Special Considerations

If a patient has neurologic deterioration due to a spinal metastasis, surgical decompression is considered first-line therapy. Radiosurgery may be performed after surgical decompression in this case. “Separation surgery” refers to surgical procedures performed with the expectation of adjuvant radiotherapy and a central goal is creation of a safe envelope around the spinal cord (▶ Fig. 95.1).

95.7 Special Instructions, Positioning, and Anesthesia

The patient is often positioned supine. Anesthesia is generally withheld unless the patient becomes agitated, in which case low-dose benzodiazepine or narcotic may be administered. Postprocedure steroid is administered at the discretion of the treating team, should there be concern for tumor swelling and subsequent spinal cord compression.

95.8 Tips, Pearls, and Lessons Learned

Tumor local control rates with radiosurgery are as high as 96%.

95.9 Difficulties Encountered

Potential difficulties with spinal radiosurgery range widely and include planning complexity to include the tumor target, but avoid the spinal cord; patient movement during the procedure; postprocedure failure to control tumor progression; postprocedure neurological deterioration; and continued pain syndromes.

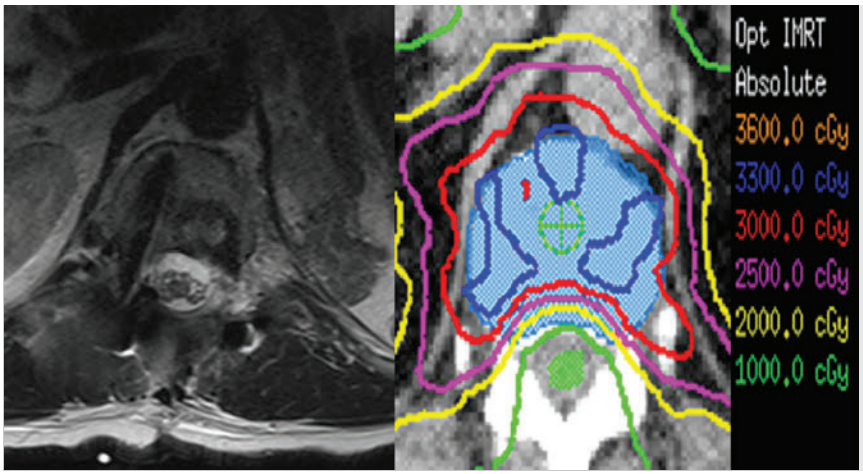

Fig. 95.1 A magnetic resonance image, T2-weighted sequence performed, axial view, postoperatively after the decompression of a metastatic epidural tumor (left). In many cases of extensive epidural disease, the goal of surgery is stabilization of the spine, and decompression of the spinal cord, where circumferential cerebrospinal fluid signal can be seen. This leaves a maximal safe distance for intensity modulated radiotherapy, a modern treatment technique that delivers a radiation dose to an irregular geometry, maximizing the dose delivered to the tumor while sparing the spinal cord (right).

95.10 Key Procedural Steps

Early radiosurgery required invasive fixation of the spinal segment to achieve accuracy of less than 1 mm. Later developments allowed for localization using radiopaque spinal fiducials that were implanted in the patient. Positioning has evolved to completely noninvasive means, such as with body frames and skin-marker fiducials.

Treatment planning consists of the use of a CT-simulator to obtain pretreatment images with radiomarkers on the patient's skin. The treatment plan is developed prior to patient positioning, often days in advance. The plan is generated with collaboration among the spine surgeon, radiation oncologist, and the radiation physicist.

Gantry-based systems such as Novalis (Brain Lab, Inc.) and Synergy (Elekta) rotate the linear accelerator around a fixed point called the isocenter. Positioning for this system is done by moving the patient table. Pretreatment positioning can be optimized by stereoscopic X-ray (Novalis), and in certain systems, adjustment in patient positioning assisted by the use of an optical camera relaying positional data with skin surface fiducials (e.g., Novalis).

Nongantry-based systems such as CyberKnife utilize multiple beam paths delivered by a linear accelerator within a mobile robotic arm, which can automatically make adjustments in space, accounting for patient movements.

Often, noninvasive radiosurgery involves patient immobilization with an immobilization cast or device such as the Bodyfix (Medical Intelligence), which is a vacuum-molded cushion with an overlying plastic foil that provides immobilization.

95.11 Bailout, Rescue, and Salvage Procedures

If the initial radiosurgical treatment fails, the next steps should be discussed with the patient and the entire multidisciplinary team. Possible next steps include repeat radiation treatments, open surgical treatment, or palliation.

Pitfalls

- Pitfalls of spinal radiosurgery include the complexity of composing a treatment plan that must include the tumor targe,t but also avoid the spinal cord. The failure to control tumor progression must be considered, as well as the possibility of postprocedure neurologic deterioration due to spinal cord involvement.

96 Surgical Removal of Intradural Spinal Cord Tumors

Paul E. Kaloostian, Ziya L. Gokaslan, and Timothy F. Witham

96.1 Description

Resection of intradural tumors is performed almost exclusively through a posterior approach. Laminectomies or laminoplasties are performed rostral and caudal to the level of the lesion and are critical to provide adequate exposure for tumor resection. Coronal exposure is also important with wide, but facet-sparing, laminectomies and laminoplasties that allow for gentle manipulation of the tumor and spinal cord if necessary. Even ventrally situated tumors can most often be approached in this fashion.

A dural opening rostral and caudal to the level of the lesion is critical. The arachnoid should initially be preserved to prevent spinal cord herniation. Opening the dura rostral to the lesion first also helps to prevent herniation of the spinal cord if the arachnoid is not preserved. Techniques to allow for gentle manipulation of the spinal cord include wide laminectomies, a lengthy dural opening, sectioning of the dentate ligaments, and in some cases, nerve root sectioning.

96.2 Expectations

Intradural spinal tumors are classified as extramedullary or intramedullary. In most cases, the extramedullary tumors are benign, and the surgical goal is complete resection. In some cases with lesions such as neurofibromas, complete resection is not possible without complete or partial transection of the nerve root of origin. If the root is one that subserves a critical function (i.e., C5 root) then consideration is given to subtotal resection. The majority of extramedullary tumors may be cured with complete surgical excision. Intramedullary tumors are less likely to be cured by surgery alone. Ependymomas, hemangioblastomas, angiolipomas, and pilocytic tumors are usually amenable to complete resection, whereas malignant astrocytic tumors require subtotal resection or biopsy followed by adjuvant therapy.

96.3 Indications

A contrast-enhancing intradural spinal lesion in a symptomatic patient is usually approached surgically for diagnostic and therapeutic purposes. Symptoms include motor or sensory deficits, sphincter dysfunction, and pain localized to the area of the lesion. Pain that is not mechanical and tends to be exacerbated by recumbency is common with intradural spinal tumors.

96.4 Contraindications

Transverse myelitis and multiple sclerosis are two disease entities that may be confused with intramedullary spinal cord tumors. Clinical history and imaging can differentiate these diseases from intradural tumors. However, if the clinical picture is not clear, then a neurologic workup for demyelinating disease should be initiated. Drop metastases are typically not approached surgically. Elderly patients who are asymptomatic may be initially followed with serial imaging. Tumors with highly aggressive behavior may be considered for biopsy and adjuvant therapy.

96.5 Special Considerations

Perioperative administration of corticosteroids is not supported by scientific evidence. However, many surgeons routinely administer up to 100 mg of Dexamethasone (Decadron, Merck & Co.) prior to resection of intramedullary tumors and continue high-dose steroids postoperatively. A subsequent slow taper is performed over 2 to 4 weeks.

For intradural meningiomas that require dural resection and for intramedullary cases in which spinal cord swelling is a potential issue, a dural patch graft may be necessary. Meticulous dural closure is paramount in the prevention of a cerebrospinal fluid (CSF) fistula or pseudomeningocele. A dural sealant is routinely placed along the suture line as well.

96.6 Special Instructions, Positioning, and Anesthesia

Patients are placed in the prone position, and the chest is well padded. A Mayfield cranial clamp is used for cervical and upper thoracic lesions. Perioperative corticosteroids and broad-spectrum antibiotics are routinely administered to all patients. The horseshoe adapter to the Mayfield is avoided to prevent skin breakdown on the face or ocular pressure leading to ocular ischemia that can be observed during prolonged cases in the prone position with this device.

96.7 Tips, Pearls, and Lessons Learned

For intramedullary spinal cord tumors, the dissection is usually begun at the middle portion of the neoplasm where the lesion is the bulkiest (**Video 96.1**). Dissection in this location is least likely to result in injury to the surrounding neural tissues.

For lesions with tumor-associated cysts, laminectomies or laminoplasties to provide exposure of the cyst outside the area of the solid tumor component are not necessary. The cyst walls are typically nonneoplastic, and complete tumor resection results in the disappearance of the cyst. Intraoperative monitoring with epidural motor evoked potentials (MEPs) may be helpful as a way to avoid rather than merely detect irreversible neurologic injury. With experienced electrophysiologists, spinal epidural MEPs are a reliable predictor of postoperative outcome. All patients should be followed with plain radiographs for the development of postlaminectomy kyphosis. Children less than 3 years of age, those with preoperative deformity, and those with preoperative neurologic deficits are at greatest risk. Laminoplasties may be used in adults as well as children, and in

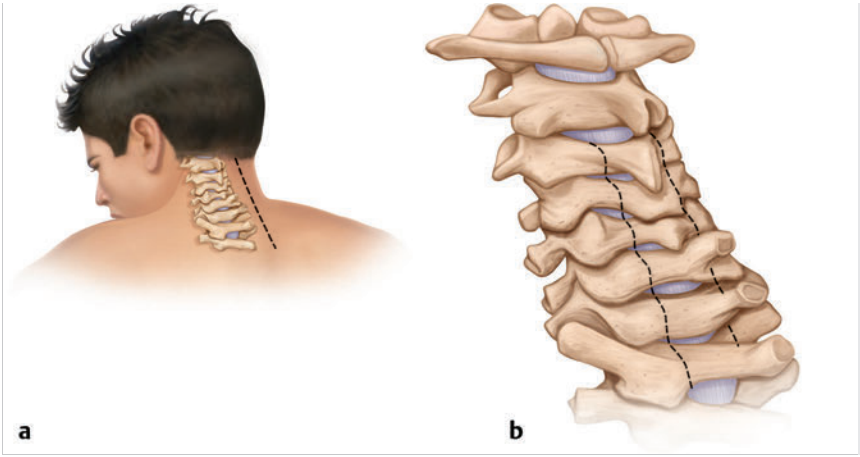

Fig. 96.1 **(a)** Intraoperative illustration of a patient with a C4–C7 ependymoma. The skin incision is marked. (**b**) The laminectomy is extended one level above and below the tumor zone.

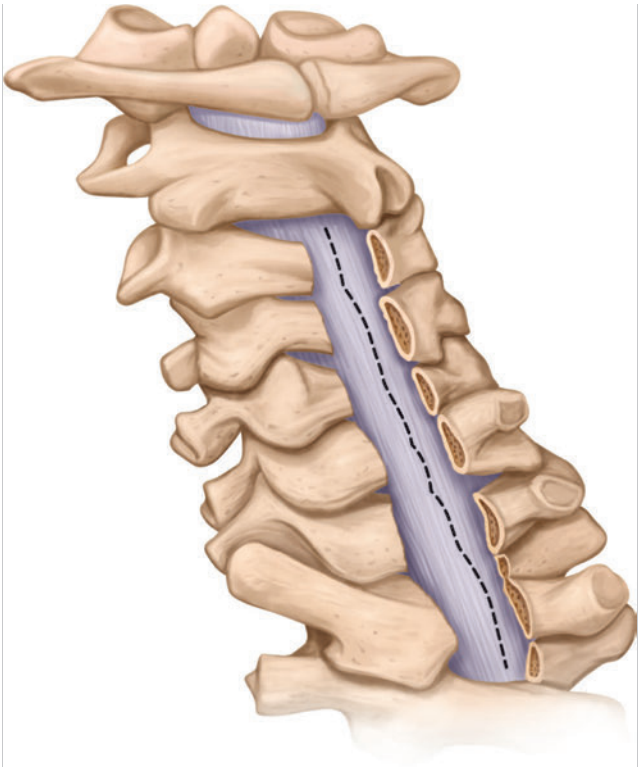

Fig. 96.2 The durotomy is completed and the arachnoid is incised.

those patients at high risk for the development of postlaminectomy kyphosis. Titanium miniplates can be used to reconstruct and stabilize the lamina. However, in our experience, laminoplasty has not been shown to prevent postlaminectomy kyphosis. We have noticed that laminoplasty appears to lessen the risk of postoperative pseudomeningocele and CSF fistula.

96.8 Key Procedural Steps

Continuous somatosensory evoked potentials (SSEPs) are monitored in all patients. MEPs are monitored as described above when a good baseline may be followed. Although SSEPs and MEPs are thought to be predictive of postoperative outcome at centers with extensive experience, this finding remains controversial.

A standard midline skin incision is fashioned with subsequent subperiosteal dissection of the paraspinal muscles (▶ Fig. 96.1 a). Laminectomies/laminoplasties or osteoplastic laminotomies are performed one level above and below the superior and inferior poles of the tumor (▶ Fig. 96.1 b). Large moist cottonoids are placed along the edges of the paraspinal muscles. Intraoperative ultrasonography is commonly helpful prior to dural opening for intramedullary tumors to determine if the tumor is sufficiently exposed rostrocaudally.

A midline durotomy is performed rostral to the superior pole of the tumor and carried inferiorly. Dural tack-up sutures are placed to tent the dural edges laterally to the muscles. The arachnoid is preserved and opened separately under microscopic guidance (▶ Fig. 96.2).

Finding the midline is important for minimizing neurologic morbidity, but may be difficult secondary to spinal cord rotation or distortion from the tumor. The posterior median sulcus may be estimated by inspection of the dorsal root entry zones bilaterally or by identifying the convergence of very small vessels in the midline. A midline myelotomy is started at the area of maximum cord enlargement and is extended to expose the tumor in its entirety. We have used dorsal column mapping by stimulating the cord directly and recording SSEPs from the scalp to identify the midline in cases in which the spinal cord is distorted.

The dissection is initiated in the midportion of the tumor (▶ Fig. 96.3). This region is the safest with respect to risk of neurologic injury. Microdissectors are used to gently spread the posterior columns. Pial traction sutures are used to maintain gentle traction on the myelotomy. With a portion of the tumor exposed, a frozen section or touch prep is obtained. The results of the biopsy may change the goals of the subsequent resection. High-grade lesions may be biopsied or debulked with the notion that adjuvant therapies will be required postoperatively. Low-grade glial tumors and ependymomas are more aggressively approached. Ependymomas are usually well circumscribed, and smaller lesions can be resected en bloc. Larger lesions are more challenging with regard to en bloc resection, particularly at the poles of the tumor.

We recommend en bloc resection when possible for several reasons (▶ Fig. 96.4). En bloc resection reduces the potential for tumor spillage while avoiding intralesional bleeding. With reduced bleeding, a better surgical plane is maintained. With some larger tumors, en bloc resection is not possible and piecemeal resection is performed.

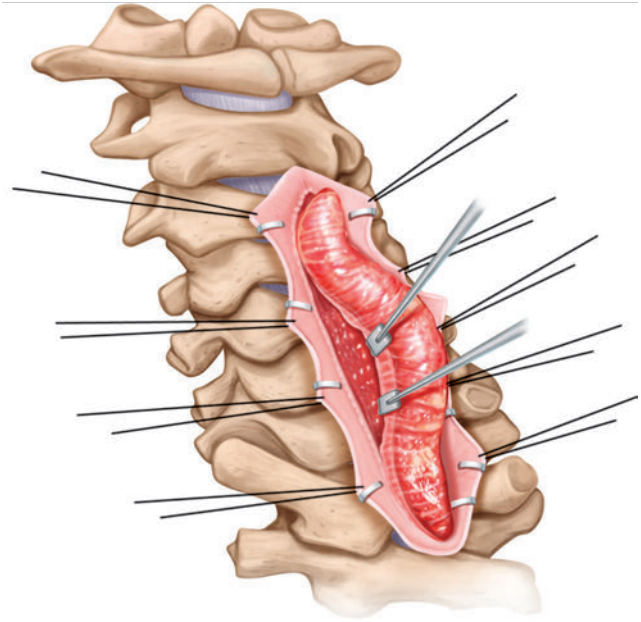

Fig. 96.3 Tumor dissection is initiated in the middle portion of the tumor, which is the bulkiest.

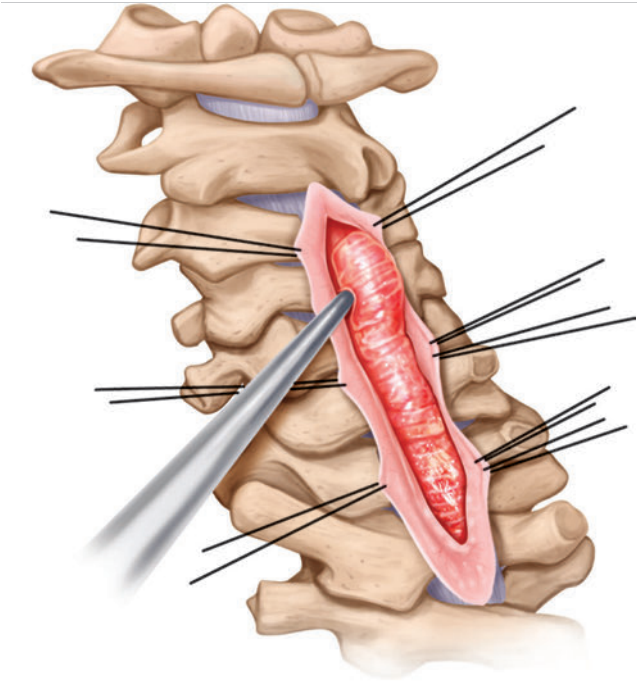

Fig. 96.4 The rostral pole of the tumor is dissected to allow for *en bloc* resection of the tumor.

Tumor resection or dissection along the anterior median raphe is often difficult because of tumor adherence to this thinned-out portion of the spinal cord (▶ Fig. 96.5). Great caution must be taken in coagulating vessels in this location that frequently represent small branches of the anterior spinal artery that penetrate the tumor. Following tumor resection, intraoperative ultrasonography is utilized to assess the extent of resection.

96.9 Bailout, Rescue, and Salvage Procedures

Spinal deformity may progress to result in neurologic compression and deficit. Therefore, frequent postoperative plain film imaging is important to recognize spinal deformity early in its course. Spinal deformity should be treated aggressively with reduction and fixation. Limiting the laminectomy and avoiding denervation or disruption of the facet joints may reduce the likelihood of this complication. However, limiting the laminectomy should not be done at the expense of limiting the safe resection of tumor.

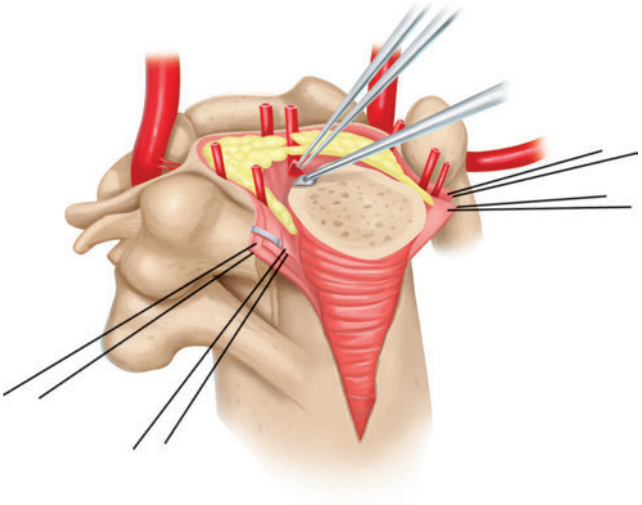

Fig. 96.5 Great caution must be exerted while coagulating branches of the anterior spinal artery supplying the neoplasm along the anterior aspect of the cord.

Pitfalls

- Paralysis following resection of an intramedullary spinal cord tumor is most commonly associated with the degree of preoperative deficit and less commonly a function of tumor histology or extent of surgical resection. A dense preoperative motor deficit has the highest likelihood of becoming a permanent deficit postoperatively. It follows that it is imperative for patients with a known intramedullary spinal cord tumor to undergo surgical resection prior to the progression of motor deficit.
- Impaired joint position sense is a potential complication that can be functionally debilitating. Careful placement of the myelotomy in the posterior median raphe with limited dissection/traction of the posterior columns may help prevent this problem.
- Spinal deformity represents a significant postoperative complication, particularly in children. Recognition of postoperative deformity and differentiation from tumor recurrence has subsequent treatment implications.
  - In children, osteoplastic laminotomy *may* minimize the incidence of postoperative kyphoscoliosis.
  - Tumor resection in conjunction with instrumented stabilization is sometimes performed in patients who are felt to be at high risk for postoperative kyphosis.
  - Spinal instrumentation, however, may limit postoperative magnetic resonance imaging capabilities.

Section XVIII

Bone Grafting and Reconstruction

97 Anterior and Posterior Iliac Crest Bone Graft Harvesting *364*

98 Autologous Fibula and Rib Harvesting *366*

XVIII

97 Anterior and Posterior Iliac Crest Bone Graft Harvesting

Alexander T. Brothers, Alexander R. Vaccaro, and Brett A. Taylor

97.1 Description

When harvesting autologous anterior or posterior iliac crest bone graft for spinal reconstructive surgery, the minimizattableion of morbidity and the optimization of structural integrity should be prioritized.

97.2 Key Principles

Autograft can be reliably and easily harvested from the anterior and posterior iliac crest. Tricortical strut autograft is most easily harvested from the anterior crest, while the largest volumes of cancellous autograft can be harvested from the posterior crest.

97.3 Expectations

Autologous bone graft is the gold standard for bone grafting and is expected to result in earlier fusion-site consolidation and decreased rates of fusion-site non-union.

97.4 Indications

Harvesting iliac crest bone graft is indicated for anterior or posterior cervical, thoracic, or lumbar fusions.

97.5 Contraindications

Harvesting iliac crest bone graft is contraindicated in patients with metastatic disease to the pelvis, soft tissue compromise overlying the graft site, and in skeletally immature patients when bi- or tricortical graft is required. Caution should be taken in patients with pelvic fractures or ligamentous disruption, previous iliac crest bone graft harvesting, or in morbidly obese patients.

97.6 Special Considerations

97.6.1 Posterior

The superior cluneal nerves provide cutaneous sensation to the buttocks and course over the posterior iliac crest beginning 8 cm lateral to the posterior-superior iliac spine (PSIS). They are oriented in a longitudinal direction; therefore. a limited vertically directed incision approximately two to three fingerbreadths from the midline should be made. The posterior iliac crest may also be exposed through subcutaneous dissection above the lumbodorsal fascia followed by fascial splitting when the iliac crest is assessed through the primary midline incision. However, in immunocompromised or diabetic patients, a separate incision over the iliac crest may offer increased protection against a deep wound infection. A continuous 48-hour infusion of 0.5% Marcaine into the donor site through a catheter infusion system has been shown to significantly reduce perioperative and long-term donor site pain. In bone-grafting-infected recipient sites, proper technique is paramount to avoid cross-contamination; use separate instruments, a protective barrier adhesive drape, and gloves.

97.6.2 Anterior

In patients who are positioned supine, a bump placed under the buttocks on the planned side will aid in graft harvest. In approximately 10% of patients, the lateral femoral cutaneous nerve (LFCN) courses over the anterior crest 2 cm lateral to the anterior-superior iliac spine (ASIS). When harvesting a large structural graft from the iliac crest, try to stay at least 2.5 to 3 cm away from the ASIS to avoid creating a stress riser, especially in osteoporotic patients. Avoid using osteotomes to procure a bi- or tricortical graft, as they have been shown to weaken the structural integrity of the graft through microscopic stress fractures as compared to a saw. If using a retroperitoneal or thoracoabdominal approach to the lumbar spine, subcutaneous dissection performed over the abdominal musculature may be used to access the iliac crest. Bovie cauterization during initial dissection should be kept at 25 or below to prevent thermal injury to the LFCN. Reconstruction of the defect left by tricortical graft procurement with local bone significantly improves chronic donor-site pain. In bone-grafting-infected recipient sites, proper technique is paramount to avoid cross contamination; use separate instruments, a protective barrier adhesive drape, and gloves.

97.7 Special Instructions, Positioning, and Anesthesia

When obtaining tricortical strut allograft, an oscillating saw is preferred to osteotome in order to ensure maximum axial strength of the graft (due to the tendency of osteotome harvest to cause micro-fractures within the graft segment). Additionally, the anterior crest can be reached via subcutaneous dissection over the abdominal wall musculature during anterior approach to the lumbar spine, allowing for autograft procurement without an additional incision.

97.8 Tips, Pearls, and Lessons Learned

97.8.1 Anterior

When taping the shoulders down for radiographic visualization of the cervical spine, make sure to place the tape free of the harvest site. One may use a double-graft harvesting blade or a single blade when procuring a Smith–Robinson tricortical graft. The iliac crest is primarily recommended for single-level corpectomy, and may be used following a two-level cervical corpectomy; however, iliac crest alone is often not possible due to limited procurable graft volume for three-level or more corpectomy. In the thoracic and lumbar spine, tricortical iliac crest is

recommended for interbody fusion. In the lumbar spine, cancellous bone can be harvested from the iliac crest using the "trapdoor" technique for packing interbody fusion cages or allograft rings.

If the abdominal peritoneal compartment is entered during iliac crest harvest, a general surgery consultation is recommended for exploration and closure of the peritoneal defect. If the lateral femoral cutaneous nerve is injured, an end-to-end primary repair should be attempted with a 5–0 monofilament suture, supplemented by collagen-tube conduits if a defect is present.

97.8.2 Posterior

Unicortical-cancellous strips or cancellous graft is most often harvested for posterior procedures. The trapdoor technique can be utilized for cancellous bone graft harvest utilizing straight and curved curettes. The sacroiliac (SI) joint is best avoided by standing on the opposite side of the table from where the graft is being obtained. Take care to avoid violating the inner table of the pelvis with either technique. Overaggressive retraction into the sciatic notch should be avoided due to the potential for catastrophic injury to the gluteal vessels or sciatic nerve.

If the gluteal vessels are injured, do not attempt to blindly clamp them due to the proximity of neurologic and urologic structures. If vigorous bleeding occurs as a result of gluteal vessel injury, isolate the bleeding vessel and apply a vessel staple or ligature. If bleeding cannot be controlled due to retraction of the vessel into the true pelvis, the superior aspect of the sciatic notch can be resected to visualize the gluteal vessels. If this is unsuccessful, pack and close the wound and seek general surgical consultation or interventional angiography for embolization of the vessel.

97.9 Difficulties Encountered

Chronic postoperative donor site pain can be extremely challenging to manage and prophylactic measures are recommended to decrease its incidence. When harvesting cancellous autograft via the trapdoor technique, replacing the roof of the harvest site can significantly decrease postoperative pain. Additionally, ceramic composite biomaterials may be used to reconstruct the donor site of tricortical allograft, leading to similar improvements. In the immediate postoperative period, a transversalis fascial plane block targeting the L1 dermatome can completely eliminate donor site pain.

97.10 Key Procedural Steps

97.10.1 Anterior

A 2- to 8-cm skin incision should be made at least 2.5 cm lateral to the ASIS inferior to the iliac crest to avoid compression by the belt line. Bluntly dissect through the subcutaneous fascia. Incise the deep fascia off the lateral edge of the iliac crest. Elevate the periosteum and deep fascia off of the iliac crest in line with the skin incision. When harvesting cancellous bone, use the trapdoor technique and replace the roof of crest before closing. If harvesting a structural bi- or tricortical graft, mark the depth of the saw cut on the blade. Thrombin-soaked Gelfoam (Pfizer Pharmaceuticals) can be applied for hemostasis. Sharp edges should be rounded off with a bur or rasp to decrease postoperative pain. Close the periosteum, deep fascia, and skin in layers. A drain may be placed in the deep or superficial layer of closure.

97.10.2 Posterior

A limited vertical incision should be made slightly lateral to the PSIS. Bluntly dissect through the subcutaneous fascia. Sharply dissect the iliolumbar fascia off the periosteum. Dissection should not extend medially to the SI joint or inferiorly to the sciatic notch. When harvesting cancellous bone, use the trapdoor technique and replace the roof of crest before closing. If corticocancellous strips are necessary, straight or curved osteotomes may be used. Thrombin-soaked Gelfoam can be applied for hemostasis. Sharp edges should be rounded off with a bur or rasp to decrease postoperative pain. Close the periosteum, deep fascia, and skin in layers. A drain may be placed in the deep or superficial layer of closure.

97.11 Bailout, Rescue, and Salvage Procedures

If the volume of the graft is inadequate, an allograft source may be used in combination, or the contralateral iliac crest may be harvested.

Pitfalls

- Chronic donor-site pain
- Neurologic injury
- Vascular injury
- Cosmetic deformity
- Abdominal injury or herniation of abdominal contents
- ASIS avulsion fracture
- Iliac wing fracture
- Disruption of SI joint
- Superficial or deep infection

98 Autologous Fibula and Rib Harvesting

Andrew H. Milby and Joshua D. Auerbach

98.1 Description

We describe the technique for harvesting autologous fibula or rib bone grafts for spinal reconstructive procedures while minimizing donor-site morbidity.

98.2 Key Principles

Although autologous fibula and rib strut grafts are not routinely used for spinal reconstructive surgeries, they remain potential sources of long structural grafts. Autologous graft harvesting from the fibula or rib carries minimal added infection risk, achieves favorable rates of fusion, may be safely performed with minimal donor-site morbidity, and offers a potential source for vascularized cortical graft material if indicated. Autologous fibular strut grafts also have superior compressive strength compared with iliac crest and rib grafts.

98.3 Expectations

The reader should be able to apply the described techniques to safely harvest autologous fibula or rib grafts for use in spinal reconstructive procedures.

98.4 Indications

- Posterior cervical reconstruction
- Posterior occipitocervical fusion
- Anterior column reconstruction to prevent kyphosis or instability following corpectomy for infection, neoplasm, or trauma

98.5 Contraindications

- Fibula: Pre-existing ipsilateral ankle pain, instability, weakness, sensory or motor deficit, or vascular compromise
- Rib: Previous fracture or deformity, pulmonary compromise prohibiting single-lung ventilation

98.6 Special Considerations

In situations at high risk for delayed union or non-union, such as multilevel fusions, thoracolumbar kyphosis, or tumor resection with subsequent postoperative radiation, vascularized fibular or rib grafts may be indicated to provide a solid initial biomechanical construct and facilitate a quicker time to fusion. If a vascularized fibular graft is considered, it is recommended to obtain preoperative vascular imaging to evaluate for anomalous circulation or previous injury to the graft's vascular pedicle.

The fibula is a straight cortical bone that can provide a graft up to 26 cm in length. The vascular pedicle, which may be from 1 to 5 cm in length, is comprised of the peroneal artery (1.5–2.5 mm diameter) and its accompanying two vena comitantes (2–3 mm diameter).

The rib is a curved, flexible bone that can provide a graft up to 30 cm in length. The shape of the graft can be modified by the choice of the rib and section of rib excised (from flatter posterior portion to curved anterior portion) to optimize contact between the graft and recipient bed. Its vascular pedicle, which may be from 3 to 5 cm in length, consists of the posterior intercostal artery (1.5–2 mm diameter) and single intercostal vein (1.2–2.5 mm diameter).

98.7 Special Instructions, Positioning, and Anesthesia

98.7.1 Fibula

The fibular graft site can be approached using either a posterior or lateral surgical approach. The lateral approach is generally preferred: It is simpler and can be done simultaneously with the majority of anterior spinal approaches. With the patient supine, a sandbag or roll is placed underneath the ipsilateral buttock for optimal visualization of the lateral leg. A tourniquet is applied to the thigh to maintain a bloodless field. General anesthesia is typically used, with or without supplementation with a local long-acting local anesthetic.

98.7.2 Rib

The patient can be placed in either the prone position if a posterior spinal procedure is anticipated, or in the lateral decubitus position with the graft side up allowing for visualization of the rib along its entire course. In the lateral decubitus position, the ipsilateral arm is elevated anteriorly and cephalad away from the ribs and the table is flexed at the midthoracic region to increase the intercostal space. The table is tilted anteriorly to allow the ipsilateral lung to fall anteriorly. A double-lumen tube is used to allow single-lung ventilation.

98.8 Tips, Pearls, and Lessons Learned

- For posterior occipitocervical fusions in children, the rib is uniquely shaped to permit maximal graft–recipient bed contact
- In children, the rib is also an abundant source of graft material and rapidly regenerates, compared with iliac crest bone graft.
- The intercostal neurovascular bundle running on the caudad surface of the rib must be identified prior to periosteal stripping to avoid neurovascular injury.

98.9 Difficulties Encountered

- Obesity may increase the difficulty of rib localization, especially the middle ribs. Fluoroscopy or plain radiography may be used to assist in identification of the correct rib.

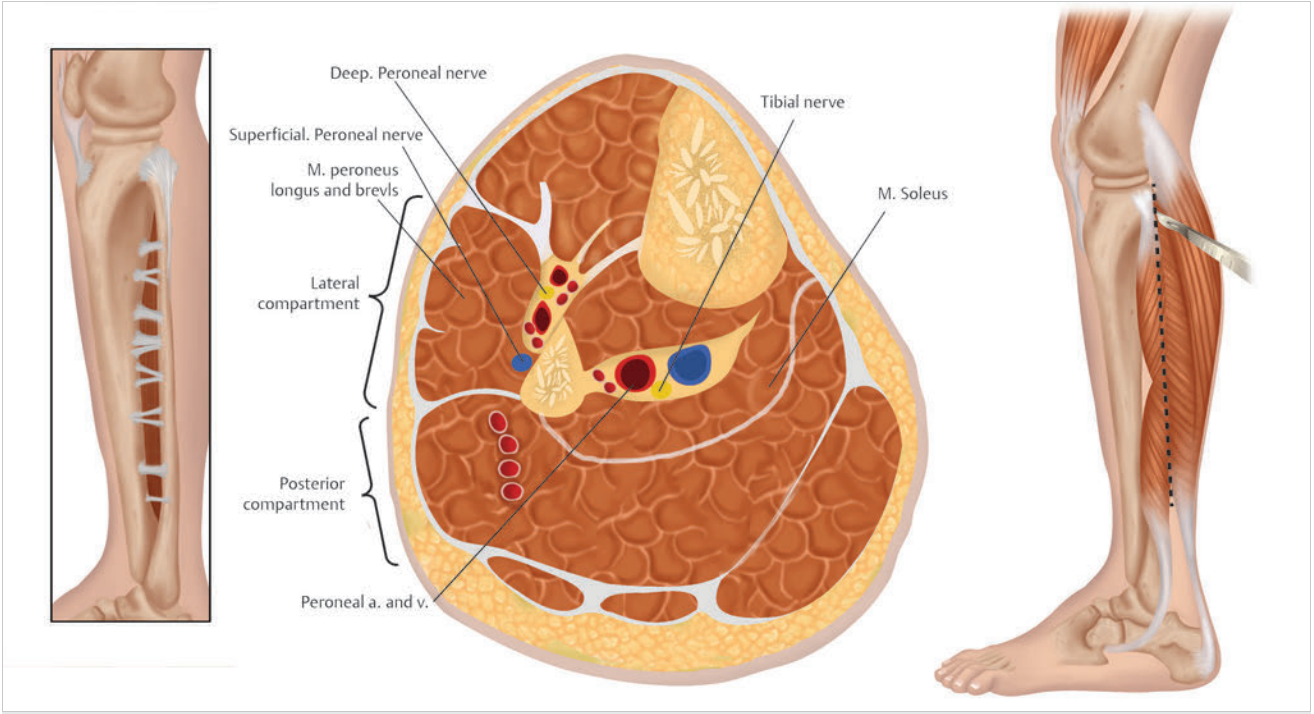

Fig. 98.1 (a–c) Identification of the fascial interval between the soleus and the peroneus longus muscles.

- After fibula harvest, the surgical team must be aware of the potential for excessive bleeding following tourniquet release, and should be prepared to reinflate the tourniquet and/or obtain intraoperative vascular surgical consultation.

98.10 Key Procedural Steps

98.10.1 Fibula Harvest

To avoid damage to the peroneal nerve, proximal fibular osteotomy should be carried out at the junction of the middle and distal thirds of the fibula; ankle instability can be safely avoided by staying 10 cm above the ankle joint for the distal fibular osteotomy. A straight lateral approach to the midportion of the fibula is used. Dissection is initially carried out between the posterior and lateral compartments of the leg. Incise the superficial fascia overlying the peroneus longus and soleus muscles (▶ Fig. 98.1), and continue to dissect in a plane posterior to the peroneus longus and anterior to the soleus muscle. The peroneal vessels lie just deep to the soleus and are almost in contact with the fibula. After identification and protection of the vessels, incise the fibular origin of the soleus muscle and retract posteriorly (▶ Fig. 98.2). Identify and protect the superficial peroneal nerve in the proximal aspect of the incision. Attention is then turned to the distal aspect of the fibula where the interval between the peroneal muscles and the more posteriorly located flexor hallucis longus is identified. The peroneal vessels travel within the substance of the flexor hallucis longus muscle and are therefore protected with careful retraction. For anterior exposure, retract the peroneal muscles anteriorly and dissect them off the fibula in an extraperiosteal plane. Continue extraperiosteal dissection distally; being sure to protect the anterior tibial artery and deep peroneal nerve anteriorly (▶ Fig. 98.3). If a vascularized graft is not required, dissection may be carried out in a subperiosteal plane to maximize protection of the neurovascular structures. A Gigli saw is used to osteotomize the fibula with careful retraction of the peroneal vessels posteriorly, and the superficial and deep peroneal nerves and anterior tibial artery anteriorly. After identification, the peroneal vessels may be ligated and divided distally to gain maximal access to the fibula, but their preservation is preferred if possible. The fibula is carefully elevated from the wound proceeding distally to proximally, while the intact pedicle is maintained proximally if a vascularized graft is to be performed. The peroneal vessels are then clipped at their origin at the posterior tibial vessels. Finally, the tourniquet is released, meticulous hemostasis is obtained, the wound is closed over suction drainage (do not close the fascial compartments for risk of compartment syndrome), and the patient is made weight-bearing as tolerated on the donor extremity following a brief period of splint immobilization for comfort. Passive stretching exercises at the ankle may help prevent postoperative contractures.

98.10.2 Rib Harvest

The specific rib, as well as the specific portions to be used, is determined by the desired shape and length of graft necessary for arthrodesis. The correct rib must then be localized, and an oblique incision is made over the rib. Dissection is continued through the superficial fascia, latissimus dorsi, and erector spinae muscles to expose the rib. The periosteum overlying the rib is circumferentially dissected off and the rib is elevated (▶ Fig. 98.4). A rib stripper is used to completely subperiosteally remove the pleural surface from the rib. Disarticulation at the costovertebral joint is then performed, and dissection is carried out to the costochondral region using a rib cutter. The rib is

Fig. 98.2 Following identification and protection of the underlying peroneal vessels, the fibular origin of the soleus muscle is carefully incused.

harvested lateral to the costovertebral joint to avoid injury to the artery of Adamkiewicz. Care is taken to remove enough bone for strut grafting and/or morselized graft, as indicated. The pleura are then inspected visually, and a Valsalva maneuver may be performed to inspect for air leaks. If no leaks are present, the chest is then closed in layers. The placement of a chest tube should be considered in cases of identified or suspected air leaks.

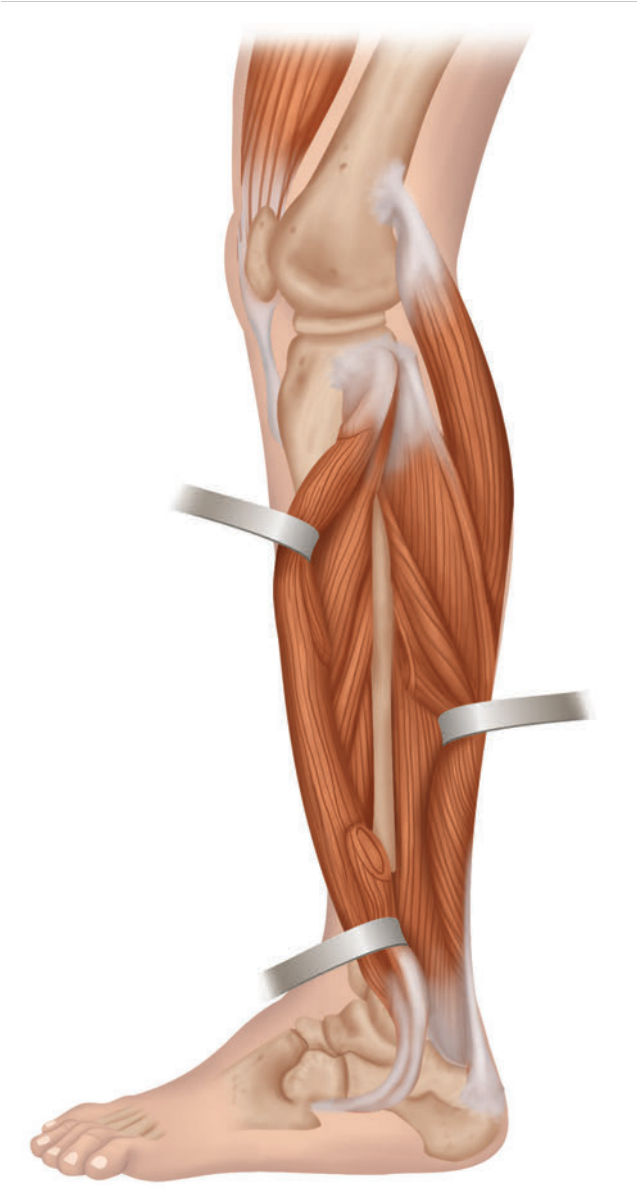

Fig. 98.3 Retraction of the anterior tibial artery and deep peroneal nerve anteriorly.

98.11 Bailout, Rescue, and Salvage Procedures

If the volume or shape of autologous strut graft is inadequate, anterior iliac crest bone graft can be used instead. Allograft bone can be substituted at any time for inadequate or insufficient autologous strut bone graft. If using rib autograft, a second rib can be used to augment the first graft. If pleural injury is noted at the time of rib harvest, a primary repair is undertaken. If ankle instability is identified following fibular harvest, syndesmotic stabilization or tibiotalar fusion may be required to restore ankle stability and prevent progressive deformity.

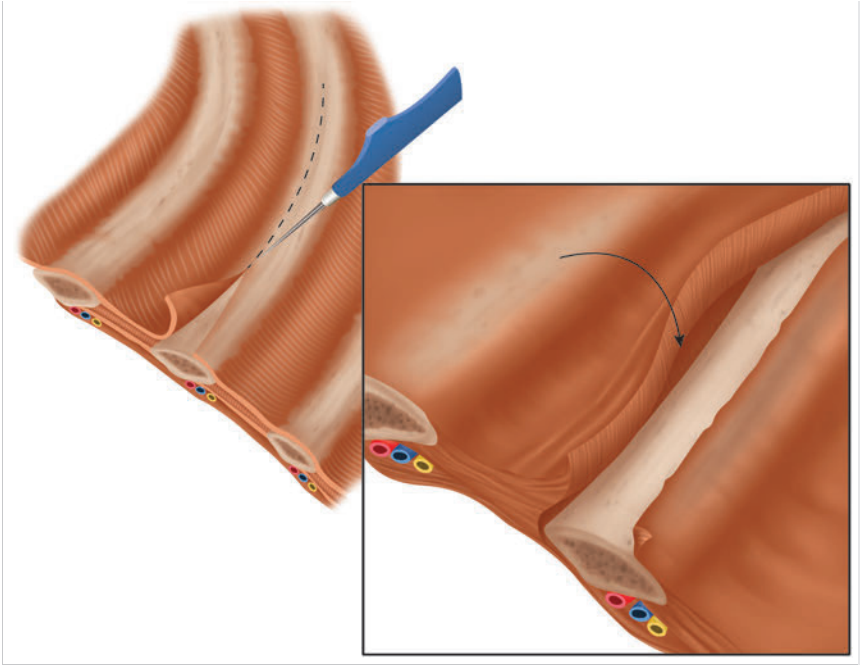

Fig. 98.4 Enter the pleura above the rib to avoid damage to the neurovascular bundle that runs along the posteroinferior rib boarder.

Pitfalls

- Fibula: Failure to adequately identify baseline ankle or lower extremity neurovascular compromise, or inability to protect the neurovascular structures during harvest may lead to ankle pain, instability, leg weakness (predominantly the leg evertors), nerve injury, muscle contractures, postoperative hematoma, pulmonary embolism, lower extremity vascular compromise in patients with aberrant vascular anatomy, and delayed wound healing due to compromised lateral skin vascular supply (peroneal artery and vein). The distal fibular osteotomy should be performed at least 10 cm proximal to the ankle joint to minimize risk for syndesmotic injury and subsequent ankle instability. Inadvertent harvest of the peroneal vessels in a patient with aberrant vascular anatomy may result in a devascularized foot, necessitating emergent revascularization. Therefore, preoperative arteriography should be considered in cases of suspected vascular compromise in the ipsilateral or contralateral lower extremity.
- Rib: Intercostal neuralgia, pneumothorax, dysesthetic chest pain, and intercostal neurovascular injury may all occur following autologous rib harvest. In 80% of patients, the artery of Adamkiewicz arises from the left side off an inferior intercostal artery and enters the intervertebral foramina near the costotransverse joints, accompanying one of the ventral roots of T9–T12. To limit the risk of injury to this artery or collaterals and resultant paraplegia, avoid ligature of a vessel close to the foramen and proceed cautiously when disarticulating a costotransverse or costovertebral joint. Consider preoperative angiography prior to left-sided approaches between T8 and T12, although the artery may enter the canal from T5–L5.

Section XIX

Spinal Immobilization

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XIX

99 Halo Orthosis Application

Kenneth C. Moghadam, Gregory D. Schroeder, and R. John Hurlbert

99.1 Description

Proper halo application creates long-term immobilization of the cervical spine, while ensuring patient safety and comfort.

99.2 Key Principles

- Proper positioning of ring and screws
- Appropriate tightening of screws
- Snug-fitting vest
- Pin-site maintenance

99.3 Expectations

Effective halo application and care should confer immobilization for complex unstable cervical spine conditions without producing pain, difficulty swallowing, or visual obscuration, while at the same time allowing patient mobility.

99.4 Indications

- Nonsurgical management of cervical spine instability secondary to trauma, degenerative disease, or infection
- As an adjunct to surgical reconstruction

99.5 Contraindications

- Frontal, temporal, or parietal skull fractures
- Scalp laceration at pin site
- Head injury necessitating craniotomy
- Major chest injury
- Life-threatening abdominal injury
- Pulmonary insufficiency

99.6 Special Considerations

Skull pins should be retorqued to 8 inch-pounds (0.90 newton-meters) at 24 to 36 hours postapplication, as ring migration is common. All other screws and straps should be checked and tensioned to their initial settings. Vest repositioning may be necessary due to minor torso shifting. The skin is cleansed in a circular fashion around each pin on a daily basis, utilizing sterilized cotton swabs soaked in normal saline. If crusts form on the skin at the pin sites, they should be moistened, but not forcibly removed so as to prevent further skin breakdown. Mild irritation of the skin at the skull pins' site is common. However, reddened, shiny, elevated skin with purulent discharge indicates local infection. Cultures should be obtained and topical antibiotics applied in conjunction with oral antibiotics. Relocation of a pin at an infected site may be necessary if the infection persists or if the torque setting cannot be maintained at a minimum of 6 inch-pounds (0.68 newton-meters).

A well-fitted vest is essential to maintain spinal alignment. Frequent, follow-up visitation is required to ensure pin site health, vest position, and wear as well as patient compliance. Typically at the terminus of care, which may be 12 weeks or longer in duration, radiographic evidence is obtained to determine fusion or fracture healing of the affected region. The positioning rods may be removed to allow for flexion and extension films without removing the ring.

Removal of the halo is most easily accomplished with the patient sitting in a chair. The lock nuts securing the skull pins should be loosened first. If spinal integrity or muscle weakness is a concern, a cervical collar may be applied prior to halo ring and vest removal. To disassemble the vest, the rods are removed first and then the chest and shoulder straps loosened on one side. The patient leans forward slightly so that both vest plates can be removed in one step. After loosening the locking nuts, the anterior skull pins are loosened and backed away from the skin to at least 1 cm of clearance. An assistant may hold the ring firmly from behind the patient to reduce migration as the posterior pins are removed. It is important before removing the ring to ensure that all pins are backed away with sufficient clearance to prevent laceration to the skin. An antibiotic ointment is applied to reduce bone exposure to air at the pin sites. The antibiotic is reapplied 24 hours later. Normal skin closure occurs within 36 hours. Patients should avoid washing their hair until this time.

For cardiac emergencies, halo manufacturers either create a precreased area on the anterior vest to facilitate access to the chest for compression or electrostimulation, or they supply a box wrench to loosen the anterior rods allowing access to the chest. After the emergency, the vest may be reapplied, refastened, or replaced according to the manufacturer's specifications.

99.7 Special Instructions, Positioning, and Anesthesia

The superstructure allowing connection to the halo ring is applied to both the anterior and posterior vest plates, composed of support rods and connectors. The anterior vest is applied to the anterior chest wall and secured to the halo ring. The patient is gently log rolled to one side using spinal precautions, and the posterior vest is slid into position. The patient is returned to a supine attitude, and the posterior vest is fastened to the ring with the remaining rods and connectors. Vest straps are applied to firm tension at the abdomen and shoulders. It may be necessary to reposition the head for best spinal alignment. Typically, a neutral position is best; it is seen as an imaginary horizontal line from the inferior lobe of the ear to the inferior tip of the nose. Radiographic evidence is required to confirm cervical alignment.

Positioning of the vest may require special attention in certain circumstances. Morbidly obese patients may require special accommodation of vest size and positioning, as it is important to ensure that the distal border of the anterior vest is superior to the diaphragm, leaving sufficient space for abdominal expansion for respirations. Emaciated patients require attention to

potential pressure points to reduce risk of skin ulceration. Attention to prominent scapulae, clavicles, and spinous processes is appropriate to limit skin complications.

99.8 Tips, Pearls, and Lessons Learned

Surgical bed adapters are commercially available to allow fixation of the halo ring to the operating table. Once positioned on the table and fixed in the adapter, the anterior or posterior vest may be removed easily without compromise to the cervical spinal alignment. If necessary, reapplication postoperatively is easily accomplished, with the adapter maintaining the head position. Insertion of a soft (egg-crate type) padding to the vest section, under the sheepskin, is desirable to avoid skin lesions during surgical procedures.

99.8.1 Imaging

Most halo orthoses are magnetic resonance imaging (MRI) compatible; however, the manufacturer's specifications should be examined to ensure compliance.

99.8.2 Pediatric Applications

Selection of an appropriately sized ring is important. Measure the circumference of the head 1 cm above the ear and eyebrows and select the appropriate ring according to the halo manufacturer's sizing chart. In general, a closed ring is preferred to an open ring to accommodate the greater number of pin sites necessary due to immature development of the cranium. The number of pins placed into the skull and the degree to which they are tightened are age specific (▶ Table 99.1).

99.9 Key Procedural Steps

99.9.1 Ring Type and Size

Halo rings are available in two styles, open-backed (horseshoe shaped) and closed-backed (ring shaped). The open-backed ring simplifies application because the patient's head can remain flat on the bed during positioning and pin insertion. It also leaves the posterior neck and occiput well exposed if posterior surgical management is required. The closed-backed ring allows for a greater number of pin placements. Different manufacturers provide rings of different sizes. A properly fitting ring should allow for about 1 to 2 cm of clearance circumferentially from the scalp when positioned at or just below the equator of the skull.

Table 99.1 Age adjusted pin application

Patient age: Years	Number of pins	Torque Inch-pounds (newton-meters)
<5	8–12	2–3 (0.23–0.34)
6–14	6–8	4–6 (0.45–0.56)
15–17	4–6	6–8 (0.68–0.90)
Adult	4	8 (0.90)

99.9.2 Ring Application

The patient is positioned supine on the hospital bed. A positioning plate called a spoon is inserted underneath the patient in the midline of the spine so that it spans from the inferior border of the scapula to the posterior pole of the occiput. While gentle in-line traction is maintained, the patient and spoon are drawn up the bed to allow the head and neck to rest on the spoon, extending freely off the top of the bed. It is necessary to shave a 2.5-cm^2 area just behind and above the ear in preparation for the posterior (parietal) pins (▶ Fig. 99.1). The frontal and parietal pin sites are prepared with Betadine, chlorhexidine, or alcohol sterilization.

The selected ring is placed around the skull with three positioning pins tightened finger tight against the skin (▶ Fig. 99.2). When placing the positioning pins, it is best to utilize the most anterior hole to assist in midline orientation of the ring and also the first or second most posterior holes on the sides. This allows for the best positioning of the skull pins later. The ring should be at least 2 mm above the eyebrows and the superior helix of the ear. The positioning pins are tightened against the skin, ensuring that the anterior pin is aligned with the midline of the forehead. Appropriate symmetry at this point aids in the alignment of the vest later. Adhesive tape placed underneath the mandible and attached to each side of the ring laterally is beneficial to prevent migration of the ring. Any touch-up to skin sterilization can be performed at this time.

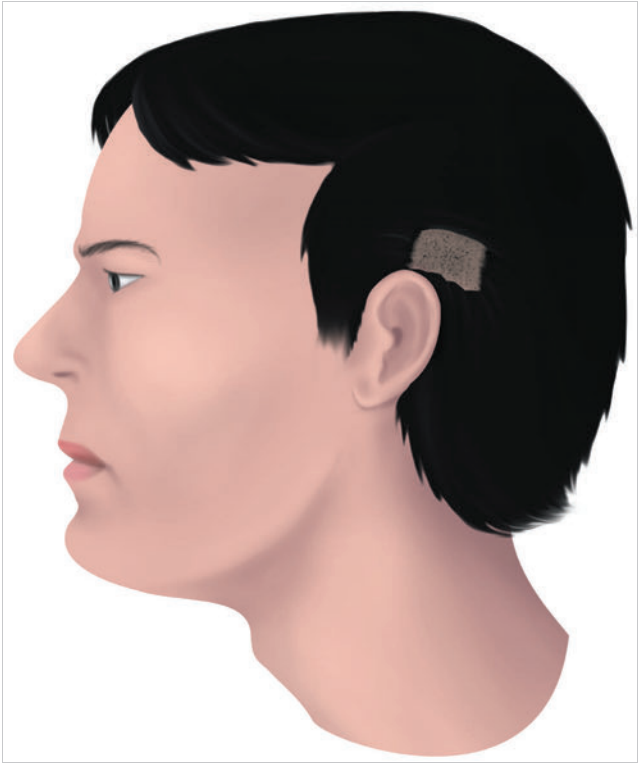

Fig. 99.1 A 2.5-cm^2 area is shaved just behind and above the pinna of the each ear to facilitate insertion of the posterior halo pins and to allow for optimum pin-site care.

Fig. 99.2 Positioning pin placement. (**a**) Coronal view. **(b)** Oblique view. **(c)** Axial view. The halo ring is held in place by three positioning pins prior to insertion of the skull pins. The positioning pins are finger-tightened against the scalp through the anterior middle and most posterior lateral holes in the orthosis, securing the ring with respect to the skull. Adjustments can be made to achieve symmetry and final positioning with respect to (1) the equator of the skull, (2) the eyebrows, and (3) the ears before the skull pins are inserted.

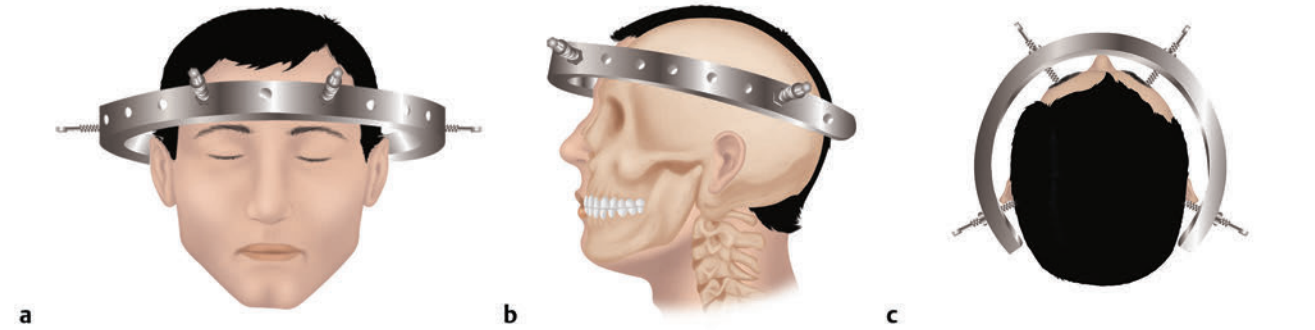

Fig. 99.3 Skull pin placement. (**a**) Coronal view. **(b)** Sagittal view. **(c)** Axial view. Four skull pins affix the halo ring to the skull, one above each eyebrow and one just above and behind each ear, so that the ring is approximately 5 mm above each eyebrow and each ear pinna, at or below the equator of the skull. The ring should clear the scalp circumferentially by 1 to 2 cm.

Skull pins are placed just above the eyebrows, usually in the first or second ring holes lateral to the midline anterior positioning pin. Special attention is suggested to stay in the lateral third of the eyebrow to avoid the supraorbital nerve. Posterior skull pins are typically placed in the last available posterior hole of the open ring, adjacent to the posterior positioning pins (▶ Fig. 99.3). The skull pins are advanced to within 1 mm of the skin in their selected positions, and the skin and periosteum are infiltrated with 2% Xylocaine. All pins are hand-tightened through the skin, allowing the person applying the halo to feel the solid purchase of each pin on the skull. Ensure that the patient's eyes are firmly closed during insertion of the anterior skull pins to prevent elevation of the eyebrows and to allow the eyelids to completely cover the eye when the patient is at rest. A torque wrench set to 8 inch-pounds (0.90 newton-meters) is utilized to complete the tightening on the skull pins in a "cross" (front-to-back and back-to-front) pattern advancing each pin one-half to three-quarters of a turn at a time until final torque is reached. Visual inspection is necessary during this procedure to ensure that the ring does not migrate. Once the skull pins are properly set, the lock nuts are applied to prevent pin loosening. The positioning pins and pads are removed, and the patient is lifted back down on the bed, with a physician controlling the head at all times.

Cranial defects or conditions such as osteogenesis imperfecta may necessitate default to a closed-backed ring and a pediatric (multiple) pin protocol.

99.10 Bailout, Rescue, and Salvage Procedures

If a patient cannot tolerate a halo orthosis, two viable alternatives are surgical fixation or the use of a hard cervical orthosis. Which of these options is best depends on the indication for using the halo. Although in previous decades halo use was very common is cervical trauma, there is now a substantial body of literature demonstrating that the morbidity and the mortality of a halo, particularly in geriatric patients, is significantly more than surgical fixation. Similarly, prior to the advent of cervical lateral mass fixation, a halo was commonly used after a multilevel cervical corpectomy; however, now the use of lateral mass fixation has obviated the need for the halo in many of these patients.

Pitfalls

- Failure to have patients close their eyes during placement of the anterior pins may tether the skin and prevent the patients from being able to close their eyes.
- Anterior pins located more medial than the lateral third of the eyebrow can damage the supraorbital nerve.
- Failure to retighten the pins 24 to 36 hours after halo application will often result in loose pins that can migrate.
- Halo use in elderly patient is often not advised.

100 Closed Cervical Traction Reduction Techniques

Gianluca Vadalà, Fabrizio Russo, and Vincenzo Denaro

100.1 Description

The management of cervical spine dislocations is extremely challenging. Gradual closed skeletal weight reduction represents a useful technique to restore spinal alignment and the diameter of the bony canal after traumatic cervical fractures and cervical facet dislocations. Performing early cervical reduction eliminates bony compression and improves blood flow to the spinal cord, minimizing the harmful effects of ischemia and potentially leading to improved neurologic outcome.

100.2 Key Principles

- Early closed reduction of cervical spinal fracture-dislocation injuries is recommended in awake, alert and oriented patients.
- Closed reduction in patients with an additional cervical rostral injury is not recommended.
- Magnetic resonance imaging (MRI) of patients who fail attempts at closed skeletal reduction is recommended.

100.3 Expectations

The goal of closed cervical traction is to restore and maintain normal spinal alignment, providing temporary stabilization and indirect decompression of the spinal canal. This potentially allows for improved neurologic recovery and prevention of further neurologic injury. Traction is often a temporary measure, until more definitive management (usually surgical stabilization) is performed.

100.4 Indications

The most common indications for closed cervical traction reduction are unilateral or bilateral facet dislocations. Weights ranging from 10 to 120 pounds are frequently required to obtain a reduction of malaligned spinal elements following a dislocation. Lower serial traction weights (5–30 lbs) are frequently used in the setting of displaced odontoid fractures, traumatic spondylolisthesis of the axis, rotatory atlantoaxial subluxation, basilar invagination, and cranial settling. Traction may also be used effectively in other nontraumatic cervical spine conditions that result in instability or deformity such as tumors, infections, rheumatoid arthritis, and late post traumatic kyphotic deformity or instability.

100.5 Contraindications

Closed skeletal reduction is not appropriate in patients who are not alert and cannot participate in their neurologic examination, in patients with certain cranial fractures, or if the patient becomes hemodynamically unstable. Moreover, longitudinal traction is contraindicated in extension distraction injuries.

100.6 Special Considerations

Physicians involved in the treatment of cervical spine injuries must be aware of the possibility of multiple noncontiguous levels of spinal injury before attempting closed reduction of any cervical fracture or dislocation. This requires a thorough history and physical examination, as well as complete imaging of the spine in an orthogonal manner to identify all levels of anatomical and neurologic injury. The anatomical abnormality can be identified through use of various imaging modalities. A lateral cervical spine X-ray represents the quickest and most helpful screening modality to identify cervical malalignment. Good-quality X-rays (including a Swimmer's view, if needed) are necessary to visualize the lower cervical spine to the level of the superior end plate of T1. If a focal rotational deformity, indicative of a unilateral facet joint dislocation, is found on the lateral radiograph, it is useful to discern which facet is dislocated prior to traction application. This can be done clinically by examining head rotation, or radiographically. On the anteroposterior plain X-ray, the more cephalad spinous process is rotated toward the side of the dislocated facet joint. However, if there is fracture of the posterior elements, the spinous process direction might be deceptive. In this case, oblique X-rays should be obtained without moving the neck. Computed tomography (CT) is usually performed to identify anatomical abnormalities when plain X-rays are inadequate or unrevealing. The use of MRI prior to the reduction of a traumatic cervical dislocation is still controversial. The controversy is whether there is need to obtain prereduction MRI to determine if there is a disk herniation. Several surgeons state the necessity of MRI to confirm the presence or absence of a herniated disk to prevent further spinal cord damage during the reduction. However, the value of this information compared to the risk of increased time to reduction has not been established. Indeed, others argue that as long as the patient is awake and alert, closed skeletal traction reduction can be performed safely. Some physicians recommend prompt reduction without MRI in awake patients with a cervical fracture or dislocation and a significant neurologic deficit (< grade 3/5 in more than one half of the key myotomes caudal to the level of injury according to the American Spinal Injury Association [ASIA] Impairment Scale). Magnetic resonance imaging is performed in these patients after reduction to facilitate surgical planning. In those cases of bilateral or unilateral facet injury and nonsignificant neurologic deficit (≥ grade 3/5 in more than one half of the key myotomes caudal to the level of injury) some physicians recommend to perform an MRI even if the patient is alert. Other physicians never order MRI in alert and cooperative patients, while others order MRI regardless of alertness and presenting neurologic status.

100.7 Special Instructions, Positioning, and Anesthesia

Once the type of displacement is identified, the axis of traction needs to be determined. Frequently, in cases of unilateral or

bilateral facet dislocations, the traction should be applied to gently flex the neck. It is not unusual to apply a 30- to 45-degree flexion moment to begin the process of realigning the spine. Bivector traction, that combines both a longitudinal and flexion vector force, is often useful to obtain an efficient reduction in cases of displaced odontoid fractures. In patients with basilar invagination in the setting of rheumatoid arthritis, longitudinal low-weight traction (10–20 lbs) often suffices. Extension-type injuries require particular care because they are extremely unstable, and even a small degree of weight may result in excessive interspace distraction. In general, only a gentle graded flexion vector is used in extension-type injuries, or patients may be reduced in a halo vest with manual halo ring flexion.

Different devices have been used for closed cervical traction reduction. Depending on the condition of the patient, the level of injury, type and degree of tissue damage, different devices (cranial tongs, head-halters or halo rings), and variable amounts of traction weight are required to realign the cervical spine. The head-halter is noninvasive and easily applied, but it can only be tolerated for a short period before making it unsuitable for reduction of fracture deformities and dislocations. The halo ring is composed of four-pin fixation perpendicularly applied directly to the skull with low holding power against longitudinal traction. Cranial tongs, such as Gardner–Wells tongs, are currently the most used for reduction of cervical spine fracture and fracture dislocations because they allow the application of large traction forces to the skull and cervical spine.

100.8 Tips, Pearls, and Lessons Learned

In general, more weight is required to reduce a unilateral facet dislocation than a bilateral dislocation. Indeed, the intact nondislocated facet of the unilateral injury provides a significantly greater resistance to distraction with longitudinal traction than the bilateral injury without any intact facet capsule and supporting ligaments. Reduction weights of 75 pounds and over are fairly common in reduction of a unilateral facet dislocation and fairly uncommon in reduction of a bilateral dislocation.

If progressive weight is applied, but reduction is not possible, and there is no change in position of the dislocated vertebrae, a decision must be made whether to pursue further closed reduction. Additional time under traction is often helpful to allow muscular relaxation and may allow reduction to occur. Furthermore, intravenous small doses of diazepam may help to reach this goal. Axial traction alone is not enough to reduce a dislocated facet joint(s). A flexion vector is necessary to help unlock of facet joints, usually in the range of 30 to 40 degrees. A careful neurologic exam should be performed after every weight increase or change of direction of the traction vector. As soon as cervical distraction has progressed to the point where the articular facets are perched, a slight extension movement can be applied to the cervical spine by replacing the springs on the frame and/or placing a small roll between the shoulder blades to gain some cervical extension. The traction weight is then reduced and X-rays are obtained.

100.9 Difficulties Encountered

If, during the process of reduction, worsening of a neurologic deficit occurs, the attempt at closed reduction is terminated. Immediate MRI is performed and surgical treatment is undertaken.

Moreover, disk herniations in cervical spine dislocations before and after reduction are very common. The presence of an intervertebral disk herniation seen on MRI following a cervical spine dislocation has been implicated as the cause of neurologic worsening in some patients. However, no sustained neurologic worsening has been reported in an alert, awake, and cooperative patient while undergoing a closed traction reduction.

100.10 Key Procedural Steps

Gardner–Wells tongs are applied under local anesthesia. The position of the placement of the cranial tongs is crucial (▶ Fig. 100.1). The skin is prepped in a sterile fashion and infiltrated with an anesthetic down to the skull periosteum. The pins are applied below the equator of the skull, about 1 cm superior to the pinna of the outer ear. The pins are tightened by hand until the indicator on the spring-loaded side protrudes about 1 mm and retightened 24 hours after their application, until the indicator along the protruding stem is again flush with the flat surface of the pin. They should not be retightened after this. Placement of the tongs more anteriorly or posteriorly applies an extension or flexion moment to the cervical spine, respectively. Tong placement should be posterior to the neutral axis in unilateral or bilateral facet dislocation. Traction in this setting results in a flexion moment to the spine and "unlocks" the dislocated facet(s). On the other hand, a more anterior tong placement will result in an extension moment on the spine and a more difficult time reducing the facet(s), requiring additional traction weight to obtain a reduction.

The patient is then positioned in a reverse Trendelenburg position. It allows the patient's body weight to counteract the pull of traction weights. Initially, a 5- to 10-pound weight is applied and the first cervical lateral X-ray is obtained (▶ Fig. 100.2). The first X-ray must be studied for (1) excessive distraction at the level of the injury; (2) position of the head, to ensure the vector of traction is correct; and (3) most importantly, to make sure that no occult instability exists, especially at the occipitocervical junction. Weights are then added in 5- to 10-pound increments at 10- to 20-minute intervals to allow muscle relaxation and soft tissue creep. A thorough neurologic examination and lateral cervical X-ray must be performed after each weight increase (see **Video 100.1**). To avoid overdistraction, smaller weight increments (i.e., 5 pounds) should be used. If overdistraction or a significant change in the neurologic exam occurs, the weights should be quickly removed.

100.11 Bailout, Rescue, and Salvage Procedures

A closed manipulative procedure may assist in the final stages of cervical reduction, but should only be performed by an

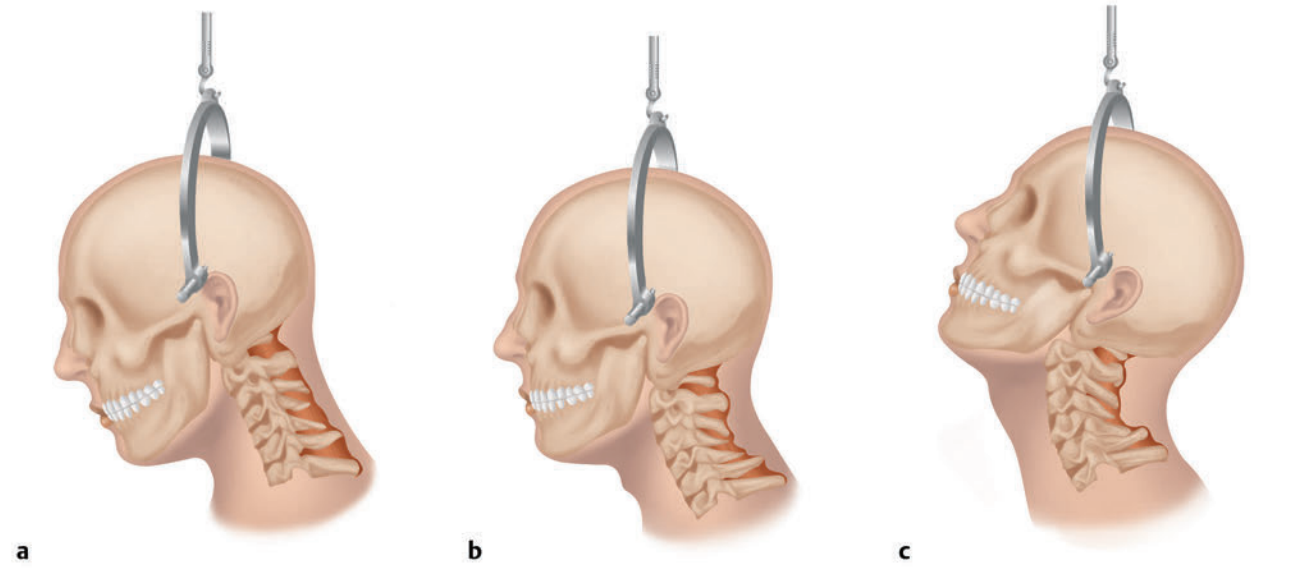

Fig. 100.1 Proper fixation points for Gardner-Wells tong application. (**a**) Posterior placement of tongs to produce flexion of head. **(b)** Normal placement of tongs to produce straight traction. (**c**) Anterior placement of tongs to produce hyperextension of head.

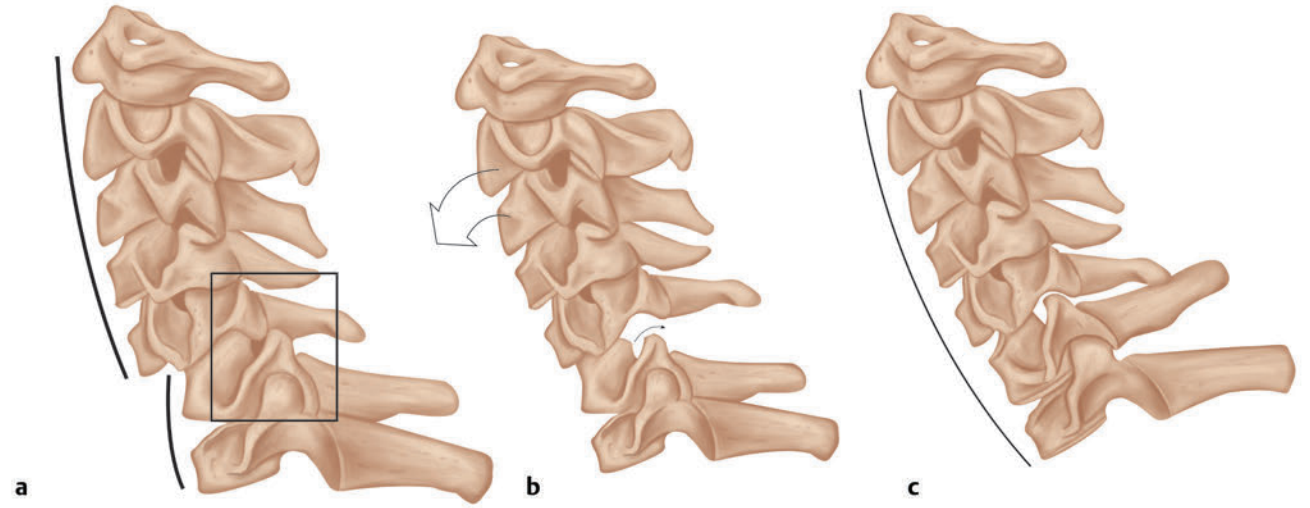

Fig. 100.2 Bilateral facet dislocation reduced with serial weights. (**a**) Initial illustration demonstrating a bilateral facet dislocation. **(b)** After placing of weight in a serial fashion, the facets are "unlocked." (**c**) Final illustration demonstrating a successful reduction.

experienced surgeon. Before any closed manipulative procedure is performed, the facets must be at a minimum perched. If a reduction maneuver is performed without the facets in this distracted position, the reduction will often be unsuccessful and may potentially result in unnecessary spinal cord compression.

For manipulation of a unilateral facet dislocation, the physician grasps the tongs with both hands while standing above the head of the patient. The physician applies compression on the located facet side and then turns the neck gradually toward the dislocated facet about 30 to 40 degrees past the midline. If any resistance is felt, the manipulation should be stopped. A forced manipulation may result in neurologic embarrassment or a facet fracture. Usually, with a successful reduction, a pop or click is heard or felt. A lateral X-ray should then be obtained, and if adequate reduction is achieved, a small roll is placed under the shoulder to maintain slight cervical extension. The traction weight is then reduced to about 10 to 20 pounds.

For a bilateral facet dislocation, the manipulation maneuver is somewhat different. The spinous processes are carefully palpated, and a gap can usually be felt at the level of the dislocation. The physician can apply slight anterior pressure just caudal to the gap, as slight distraction is applied to the tongs. The head and the neck should be rotated toward one side slowly, about 30 to 40 degrees beyond the midline, then toward the midline, and finally 30 to 40 degrees beyond the midline in the opposite direction to aid in achieving reduction. The head and neck are then gently extended. If a closed reduction fails to reduce the dislocation, then an open reduction is performed after the appropriate imaging studies are obtained.

Pitfalls

- Gardner–Wells tongs are currently the most commonly used tongs for patients with cervical spine injuries. There are several complications related to Gardner–Wells tong application. These include perforation of the inner table of the skull, pin migration or pullout, and infection. Early pin migration may be due to the shape of the calvarium or due to inadequate pin tightening and torque.
- The common causes of failure of closed reduction of cervical spine dislocations and fracture dislocations include severe pain or spasm, deterioration of neurologic function during reduction, fracture fragments physically preventing reduction, and delay in the time to reduction with partial soft tissue and bony healing. When closed reduction is not successful, a MRI should be obtained and an open reduction and spinal stabilization procedure is generally considered the treatment of choice.

Section XX

Spinal Arthoplasty / Motion-Sparing Procedures

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XX

101 Nucleus Pulposus Replacement Techniques

Stelios Koutsoumbelis, David Essig, and Jeff Silber

101.1 Description

The treatment of degenerative disk disease represents a health care problem with estimated costs exceeding $100 billion annually. Structural failure of the intervertebral disk (IVD) is irreversible in adults due to age-related structural changes related to proteoglycan metabolism. Furthermore, there is limited healing potential as a result of reduced nutritional environment of the IVD and limited chondrocyte proliferation. As a result, the IVD loses its ability to function properly under physiologic loading. This may accelerate the degenerative cascade and lead to abnormal motion within the spinal functional unit, herniation of the nucleus pulposus, and spinal instability. Clinically, patients may complain of axial low back pain and radiculopathy.

101.2 Key Principles

In the normal IVD, axial loads are transferred through the viscoelastic nucleus pulposus to the surrounding anulus fibrosus. This leads to normal concordant outbulging of both the inner and outer fibers of the anulus. Loss of pressurization to the nucleus pulposus leads to a cascade of ensuing degeneration eventually leading to loss of disk height. This leads to a less efficient transfer of axial loads and discordant bulging of the inner and outer fibers of the anulus. This disjointed bulging results in greater exposure to shear forces within the anulus and ultimately decreased ability to resist compressive loads.

A variety of surgical procedures have been developed to treat ailments stemming from IVD degeneration. These include diskectomies, interbody fusion techniques, disk arthroplasty, and disk regenerative therapies. Fusion procedures, however, have yielded relatively unpredictable outcomes. There is also concern that fusion can lead to adjacent-level problems including facet hypertrophy, spinal stenosis, and ultimately potential instability. In the case of disk herniation, partial diskectomy has been demonstrated to lead to gradual loss of disk space height over time and may accelerate the progression of IVD degeneration.

101.3 Expectations

A promising alternative may involve the use of biomaterials to replace nuclear tissue at the time of diskectomy. Nucleus replacements have been introduced as a minimally invasive alternative to fusion and total disk arthroplasty for mild-to-moderate degenerative disk disease. Initial failures with this procedure were due to either extrusion through the anulus fibrosis and/or subsidence through the vertebral bodies. More recently, several biomechanical studies have been performed looking at different compatible materials as a possible solution for nucleus replacement. Dahl et al compared static nonconforming materials like polyetheretherketone (PEEK) and polyurethane implants to dynamically conforming hydrogels of different viscosities in a human cadaveric spine model. They demonstrated that a nonconforming nucleus replacement resulted in inward bulging of the anulus, which is associated with increased maximum shear strain. Malhotra et al showed that an injectable hydrogel returned segmental spinal range of motion to normal levels when compared to diskectomy alone in an ovine model. Nucleus replacements have also been shown to restore axial compressive properties.

It is the goal of nucleus replacement to retain physiologic motion of the spinal segment while simultaneously retaining the inherent stability of that segment. This should alleviate the transfer of stress to the facet joints while simultaneously tensioning the anulus to minimize further irritation to the sinuvertebral nervous network. Ideally, this can be achieved through a minimally invasive approach, thus further preserving the surrounding soft tissue stabilizers and retaining stability of the segment. The resulting restoration and maintenance of disk height will decrease shear forces on the remaining anulus, facet joints, and stabilizing ligaments.

101.4 Indications

Nucleus pulposus replacement techniques are indicated in patients with severe disability from lumbar degenerative disk disease unresponsive to conservative therapy, diskogram concordant pain, and a minimum of 5 mm of disk height.

101.5 Contraindications

Exclusion criteria include prior surgery at the affected level(s), lytic or degenerative spondylolisthesis, facet arthrosis, Body Mass Index (BMI) > 30, disk height less than 5 mm, presence of Schmorl's nodes, and significant anular fissuring.

101.6 Special Considerations

Available nucleus replacement implants are either constrained or nonconstrained. The current literature displays a biomechanical advantage trending toward usage of unconstrained devices. Constrained devices typically consist of an inner hydrogel core and outer, constraining casing of a polyethylene polymer. This provides for less creep of the device. Due to their predetermined size and shape, this design may not contact the entire surface of the adjacent vertebral end plates. Incompatibility of Young's modulus can lead to stress shielding, resulting in accelerated bone resorption at the end plates adjacent to the implant. This can predispose the implant to subsidence or extrusion. Conversely, unconstrained implants do not have a predetermined size or shape. They are injected to fill the disk space, providing the maximum surface area for stress distribution. This can lead to less implant motion and potentially fewer extrusions. Hydrogel devices are mostly made of copolymers, including polyvinylalcohol (PVA) and polyvinylpyrrolidone (PVP). In a single-center, nonrandomized prospective trial, NuCore injectable nucleus hydrogel (Spine Wave, Inc.) was used as a replacement for nuclear tissue lost to herniation and

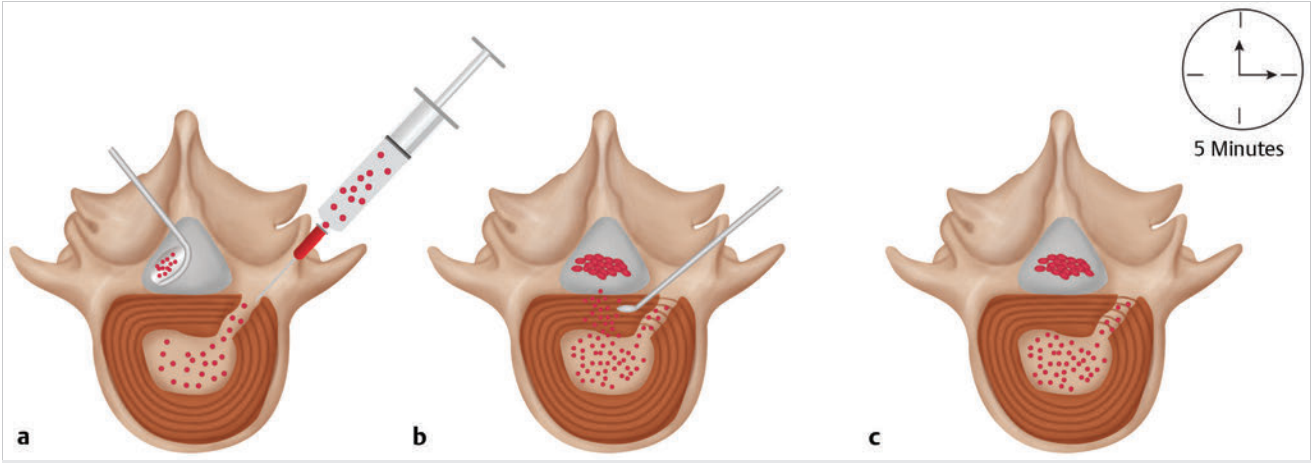

Fig. 101.1 **(a)** The nuclear replacement injectable device. (**b**) Axial view showing removal of extruded material from the neural canal. (**c**) Allow curing time for the polymer.

microdiskectomy. NuCore is an in situ curing protein polymer hydrogel that is mixed with a cross-linking agent at the time of implantation, which both fills the nuclear void and seals the anulotomy. Fourteen patients were enrolled due to a single-level herniated nucleus pulposus and were nonrespondent to conservative therapy. At 2-year follow-up there was no evidence of subsidence or extrusion in any cases, and only an average of 7% central disk height loss seen on magnetic resonance imaging and plain X-ray.

101.7 Key Procedural Steps

Specific procedural steps are outlined in the respective technique guides for each available implant type. Nearly all techniques employ a minimally invasive posterior approach that spares as much of the soft tissue envelope as possible. It is generally advisable to avoid anterior approaches so that they may be retained for subsequent surgical intervention should the need arise. A small anulotomy is made. The anulotomy is sequentially dilated to stretch the outer anulus fibers. Pituitary rongeurs are used to remove the nucleus and attention is paid to not disrupt the anulus and vertebral end plates. After removal of the nucleus, the cavity can be checked with a probe, depth gauge, or intraoperative diskogram. If using a nonconforming implant such as a hydrogel, the inserter is placed through the anulotomy to the furthest anterior portion of the diskectomy. The volume of hydrogel injected should gradually push the inserter out towards the anulotomy (▶ Fig. 101.1 a). Care should be taken to prevent extrusion of the hydrogel into the neural canal (▶ Fig. 101.1 b). The hydrogel should be given time to cure to the manufacturer's specifications (▶ Fig. 101.1 c). The anulotomy can be physically closed, dependent on device and surgeon preference. Some hydrogels, such as NuCore will self-seal.

101.8 Tips, Pearls, and Lessons Learned

Ideal patient selection for this technique is paramount. A partial diskectomy via a minimally invasive microdiskectomy with or without tubular retractor systems can be performed. It is possible that placement of a nuclear replacement device may alter the natural history of continued degeneration, especially if using a nonconforming device. Appropriate intervertebral preparation and proper placement of the device to avoid extrusion is key to optimizing long-term results. When using a hydrogel-like implant, it is important to allow proper curing time and remove extruded material from the canal.

101.9 Bailout, Rescue, and Salvage Procedures

If there is still some maintained disk height and no evidence of facet arthrosis, consideration can be given for a revision total disk arthroplasty. However, significant spinal segment degeneration and arthrosis warrants a spinal fusion. This can be accomplished via a posterolateral approach with or without concomitant interbody fusion.

Pitfalls

- Device extrusion has been described primarily with earlier implants and nonconforming agents. If extrusion does occur with neurologic sequelae, removal of the device is warranted.
- These devices should not be implanted in patients with extensive degeneration who may benefit more from a primary spinal fusion.

102 Posterior Facet Joint Replacement

Peter H. Dawson, Federico P. Girardi, Frank P. Cammisa, Jr., and Seamus Morris

102.1 Description

Posterior arthroplasty is an emerging technology aimed at addressing moderate-to-severe leg and back pain with or without instability due to spinal stenosis, degenerative spondylolisthesis, and facet joint arthrosis. The incidence of adjacent-level degeneration may theoretically be decreased by using such technologies because the index level remains mobile instead of undergoing fusion. Two devices (TOPS System, Premia Spine; ACADIA Anatomic Facet Replacement System, Globus Medical) are currently undergoing clinical trials for approval by the Food and Drug Administration.

102.2 Key Principles

The majority of posterior arthroplasty devices utilize pedicle-based fixation to reconstruct normal posterior function following decompression. The TOPS system aims to both stabilize the affected vertebrae and to replace the skeletal elements, such as the lamina and facet joints, that may be removed to achieve decompression. One device (Zyre Facet Arthroplasty System, Quantum Orthopedics, Inc.) is being developed to act as a malleable intra-articular spacer device, augmenting the anatomy of the normal facet.

102.3 Expectations

It is expected that posterior arthroplasty devices will offer effective stabilization following posterior decompression and resection of pathologic bony and soft tissue elements. In vitro testing has confirmed that some of these systems (e.g., TOPS System) maintain normal intradiskal pressures following laminectomy and facetectomy, in addition to replicating a normal range of motion of the lumbar spine. Five-year clinical results are now available for the TOPS system. In the future, posterior arthroplasty systems may be combined with an artificial disk replacement to provide a total arthroplasty solution of a diseased motion segment.

102.4 Indications

The TOPS system is intended for the treatment of moderate to severe spinal stenosis, grade I degenerative spondylolisthesis, and facet arthrosis at a single level from L3–L5 in skeletally mature patients.

Following decompression, the device is implanted to stabilize the affected motion segment while maintaining movement. The system can be used in a hybrid construction. For instance, a diseased L5–S1 segment can be fused while an adjacent L4–L5 segment with severe stenosis can be physiologically preserved with the TOPS system.

102.5 Contraindications

Contraindications are listed in ▶ Table 102.1.

102.6 Special Considerations

The TOPS system is a unitary device comprised of two titanium end-plates which interlock at an articulating core (▶ Fig. 102.1). The inferior titanium plate has a polycarbonate urethane cover and a polyetheretherketone (PEEK) ribbon to dampen the constrained motion in flexion, extension, lateral bending, and axial rotation. The design allows relative movement between the titanium plates to create ± 1.5 degrees of axial rotation, ± 5 degrees of lateral bending, 2 degrees of extension, and 8 degrees of flexion. This motion correlates to normal human motion as published in cadaver studies. The TOPS system also blocks nonphysiological posterior and anterior sagittal translation.

Table 102.1 Contraindications

Absolute	Relative
Primary diagnosis of diskogenic back pain at the index level	More than one motion segment involved in the degenerative pathology to the extent that justifies its inclusion in the surgical procedure, unless a decompression alone can be done at that level without compromising stability
Lytic spondylolisthesis at the index level	
Clinically compromised vertebral bodies at the affected level(s) due to traumatic, neoplastic, metabolic, or infectious pathology	Deformity of the spine that would compromise the implant, e.g., scoliosis > 10 degrees
Known allergy to the alloys or polymers that comprise the implant such as CoCr, titanium, polyetheretherketone (PEEK), or polycarbonate urethane	Morbid obesity defined as a body mass index > 40 or a weight > 100 lbs over ideal body weight
Back or nonradicular leg pain of unknown etiology at the index level	Dual-energy X-ray absorptiometry (DXA) bone density measured *T* score ≤ 2.0
Active local or systemic infection	Paget's disease, osteomalacia, osteogenesis imperfecta, thyroid and/or parathyroid gland disorder, and/or any other metabolic bone disease

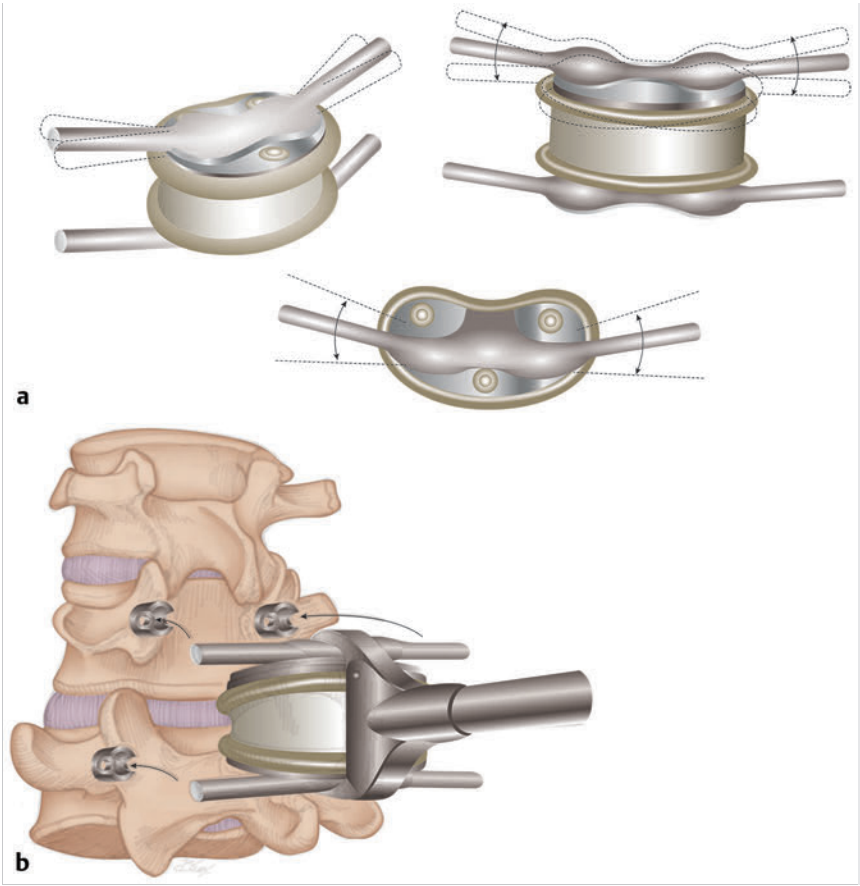

Fig. 102.1 **(a)** The TOPS system is designed to constrain axial rotation, lateral bending, flexion, extension, and posterior and anterior sagittal translation. (**b**) The TOPS device consists of two titanium end plates with a polycarbonate urethane dampening core. The four arms extending from the device are inserted in to the tulip-head connections on the pedicle screws.

102.7 Special Instructions, Positioning, and Anesthesia

The operative setup is similar to that used for a posterior lumbar fusion via a posterior midline surgical approach. Under general anesthesia the patient is positioned prone on a four-poster frame, thus allowing the abdomen to hang freely while re-creating normal lumbar lordosis.

With the TOPS system emphasis is placed on replacing those skeletal structures, such as the lamina and facet joints, that have been removed or compromised during the removal of nerve root impingement, future sources of restenosis and osteophytes. Pedicle screws may be placed before or after the decompression. The TOPS motion device is implanted thereafter. The four arms of the device are fixed to the four TOPS System surface-treated pedicle screws.

102.8 Tips, Pearls, and Lessons Learned

Patients who otherwise meet the indications for posterior arthroplasty, but either have less than 25% of their native disk height or suffer from a herniated disk at the index level should be avoided. Fusion is a better alternative to posterior motion preservation in these cases.

Care should be paid to preserve the capsule and muscular attachments surrounding the superior facet complex above the target level to prevent instability occurring at the adjacent level at a later stage.

102.9 Difficulties Encountered

All pedicle screws must lie within the same plane so that the four arms of the TOPS device fall into the saddles of the screw heads. It is also important that all pedicle screws be properly inserted within the pedicles to maximize the screw–bone integration and to minimize the chances of subsequent loosening. A proprietary pendulum and alignment gauge are used with the TOPS system, as well as intraoperative fluoroscopy and palpation following decompression, to aid with the pedicle screw and device insertion.

102.10 Key Procedural Steps

Radiographic localization of the operative level is obtained prior to the incision. The operative site is prepped and draped in the usual fashion. Operative exposure is similar to that performed for a posterior fusion, though exposure need only be performed to just lateral to the facet joint and cephalad and caudal to the target segment. The typical incision ranges from 5 to 10 cm depending on the surgeon technique for pedicle screw placement. Further intraoperative radiographic localization may be obtained following dissection down to the posterior vertebral structure.

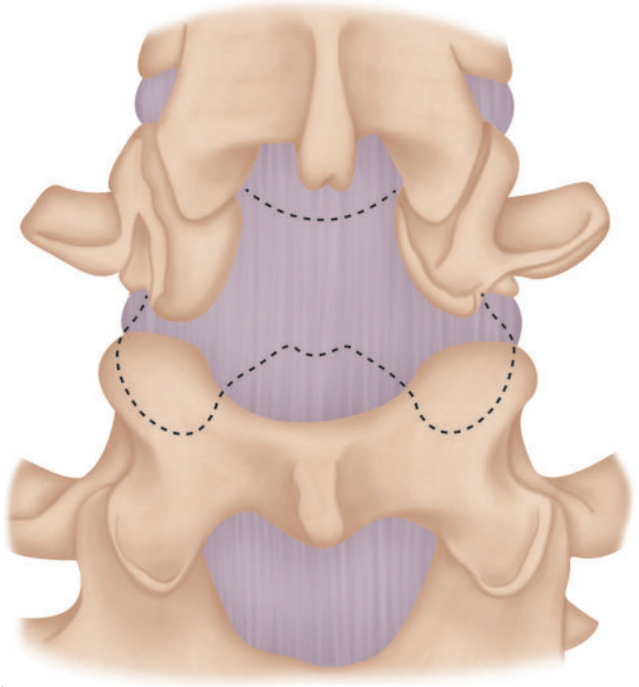

Fig. 102.2 Implantation of the TOPS device is achieved by partial or full laminectomy with facetectomy.

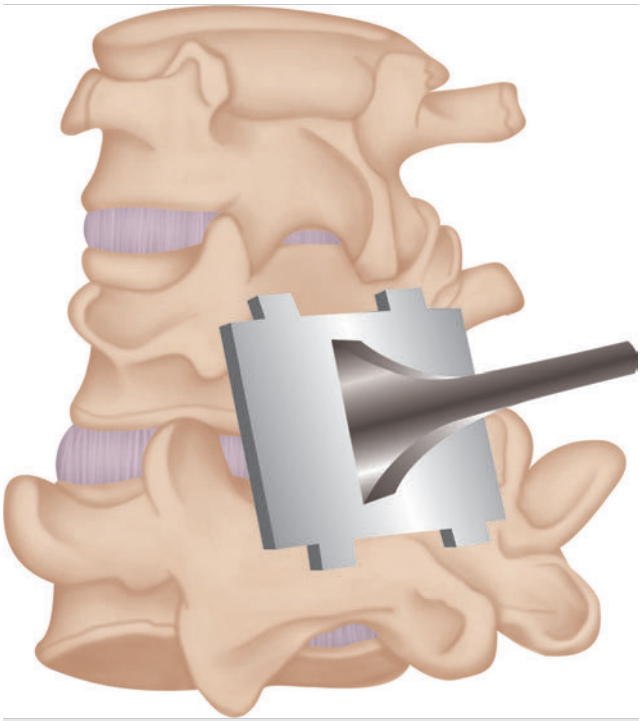

Fig. 102.3 A trial sizer can be used to estimate the extent of the necessary lamina and spinous process removal.

The pedicle screw entry points are identified at the superior and inferior vertebral levels by palpation or imaging. Insertion of the TOPS system first involves placing four surface-treated polyaxial pedicle screws, as in conventional spinal fusion surgery. The screws are cannulated for use via a percutaneous screw placement technique if desired. The goal is to have all four screws on the same plane because the TOPS motion device arms are not to be bent. An instrument confirms the orientation of the pedicle screws during insertion and another instrument serves as a decompression template, an indicator of the exact size of TOPS device required, and as a guide to advance one of the screws to bring all four pedicle screws to the same plane. The latter procedure is performed after the decompression.

A decompression of neural elements at the pathologic level is completed by a combination of a medial/full facetectomy and laminectomy, as dictated by the local pathology encountered. As the TOPS system replicates the normal functional motion and the restraining properties of the native facet joint and the posterior complex, an aggressive resection of the facet joint is possible to eliminate osteophytes and other existing or future sources of nerve root impingement and restenosis. The extent of the lamina decompression is determined by the local pathology and surgeon preference (▶ Fig. 102.2). In addition, the spinous process of the inferior vertebra of the index segment must be removed to seat the device. A device is provided to size and aid in the estimation of boney excision (▶ Fig. 102.3).

Following the decompression, leveling of the screws and templating, the proper-size TOPS device is selected. The sterile prepackaged device is mounted on an inserter and filled with sterile saline. The device is dropped into the saddle of the four pedicle screws and locked in situ. Satisfactory positioning of the device should be confirmed prior to closure by intraoperative biplanar fluoroscopy. A drain is typically left in place for 48 hours postoperatively. Patients are released from hospital without any restrictions on activity. It is not necessary to use a brace postoperatively.

102.11 Bailout, Rescue, and Salvage Procedures

A potential catastrophic intraoperative complication is an intraoperative fracture of a pedicle or pars interarticularis. This risk can be minimized by preoperative planning in terms of screw size and careful intraoperative identification and preparation of the bony structures.

Pitfalls

- Aggressive resection of the facet joint is recommended to effectively eliminate native facet joint function, as the TOPS system aims to replicate the normal functional motion restraint of the native facet complex.
- In addition, a total or near-total resection of the spinous process of the inferior vertebra of the index segment is needed to properly seat the device.

103 Posterior Interspinous Devices

Kern Singh, Steven J. Fineberg, Benjamin C. Mayo, and Frank M. Phillips

103.1 Description

There are two main categories of interspinous process implants that address symptomatic degenerative spinal conditions. Interspinous motion preservation devices (IMPDs) provide a dynamic stabilization to the functional spinal unit while allowing for indirect decompression of the spinal canal. In contrast, interspinous fusion devices (IFDs) were designed to eliminate intervertebral motion and serve as an alternative to pedicle screws and facet fixation.

103.2 Key Principles

Theoretically, an interspinous device should assist in the functioning of the diseased motion segment by providing stability and load-sharing the axial forces transmitted through the posterior elements. Posterior interspinous devices may achieve these objectives through static (IFD) or dynamic (IMPD) stabilization techniques.

103.2.1 Interspinous Motion-Preservation Devices

Certain interspinous devices have been designed for motion preservation while providing indirect decompression. Biomechanical studies have suggested that the restriction of segmental motion resulting from spinal fusion causes abnormal kinematics at adjacent mobile segments. The altered biomechanics have the potential of creating iatrogenic instability and accelerated degeneration. In an attempt to eliminate problems innate to fusion surgery, the concept of dynamically stabilizing a diseased lumbar motion segment has been proposed.

103.2.2 Interspinous Fusion Devices

Spinal fusion is commonly performed for a number of pathological conditions of the spine including spinal stenosis, degenerative disk disease, scoliosis, and spondylolisthesis. Pedicle and facet screws have been traditionally employed to stabilize the involved motion segment thereby facilitating bony fusion. The use of pedicle screws is associated with surgical morbidity and presents risk to nearby neural and vascular structures. In response to these concerns, IFDs have been evaluated as an alternative, less invasive fixation technique.

103.3 Expectations

103.3.1 Interspinous Motion-Preservation Devices

As a nonfusion technique, the IMPD is intended to relieve pain through motion-preserving stabilization. Interspinous motion preservation devices accomplish this goal by distracting the spinous processes to unload facet joints, restore foraminal height, lower intradiskal pressure, and reduce spinal extension resulting in neural compression.

Multiple interspinous implants are currently on the market and under investigation in clinical trials. Most of these devices can be classified by design as being either static or dynamic. Static devices, including X-stop (Medtronic Sofamor Danek) and Wallis (Zimmer), are made with noncompressible interspinous spacers. Dynamic devices such as coflex (Paradigm Spine. LLC) and the Device for Intervertebral Assisted Motion (DIAM; Medtronic Sofamor Danek) are compressible spacers. Proponents of both classes of motion preservation devices claim these provide varying degrees of facet distraction, decreased intradiskal pressure, and reduction in abnormal segment motion and alignment.

The X-stop is an oval titanium implant that limits spinal canal and neuroforaminal narrowing by reducing extension at symptomatic segments. The coflex (formerly “Interspinous U”) is a compressible U-shaped implant that is inserted between spinous processes in a precompressed mode. By compressing the coflex spacer prior to insertion, the device distracts against the superior and inferior edges of the spinous processes to maximize its ability to maintain position during flexion and extension. One unique claim is that the coflex can be used as a method of “topping off” the transition zone from an adjacent instrumented fusion to more mobile unfused segments. Aperius (Medtronic Sofamor Danek) and In-space (Synthes, Inc.) are more recent developments designed for less-invasive, percutaneous implantations.

103.3.2 Interspinous Fusion Devices

Interspinous fusion devices were developed to aid in stabilizing the spine in combination with an interbody fusion. These devices are designed for plate attachment to the spinous processes to achieve supplemental fixation in patients with appropriate indications. Supplemental spinous process fixation devices facilitate fusion by eliminating motion and providing structural stability. Biomechanical tests have demonstrated IFDs to be equivalent to pedicle screws and rods in restricting flexion and extension motions, but less effective in limiting lateral bending. Utilization of IFDs promotes indirect decompression and immobilization of the spinous processes of adjacent vertebrae.

The ASPEN (Lanx, Inc.) is an interspinous fusion device that secures to the spinous processes with aggressive clamping together of two plates to engage the bony elements rostrocaudally. The ASPEN has demonstrated the ability to increase foraminal height when used to stabilize interbody fusion constructs. As a cylindrical bone allograft interspinous spacer, the ExtenSure H2 (NuVasive, Inc.) is implemented alongside the Affix (NuVasive, Inc.) spinous process fixation plate and supplements the interlaminar lumbar instrumented fusion to maintain segmental distraction and stability for fusion. These devices provide a less-invasive alternative to more conventional means of fixation such as pedicle screws or anterior plates, with

less potential risk. Less postoperative pain and disability may serve to broaden the applicability of these procedures to include patients of advanced age and/or with existing comorbidities.

103.4 Indications

103.4.1 Interspinous Motion-Preservation Devices

Interspinous motion preservation devices are meant to serve as an alternative treatment for patients with degenerative spinal pathologies. However, indications for interspinous prostheses remain poorly defined and largely reflect individual surgeon biases. In general, candidates that may benefit from IMPD implantation are those that suffer from low back pain and degenerative spinal pathologies including mild-to-moderate degenerative disk disease (with no greater than a grade I spondylolisthesis), disk herniation, spinal stenosis, facet syndrome, and disk dysfunction. The definitions of symptomatic degenerative disk disease, facet syndrome, and disk dysfunction are poorly described in the literature and the ability of these diagnoses to respond favorably to these devices is equally poorly understood. Additionally, multiple manufacturers recommend that patients should be at least 50 years of age and find immediate relief from neurogenic claudication symptoms with flexion of the spine. Certain devices have attained unique approvals such as the X-stop motion-preservation device, which has been additionally indicated to treat Baastrup's syndrome (a.k.a. kissing spine). Other indications such as scoliosis and instability (poorly defined) may be exclusive to the coflex motion-preservation device.

103.4.2 Interspinous Fusion Devices

Interspinous fusion devices may be used as an adjunct in anterior, lateral, or transforaminal interbody fusions (anterior lumbar interbody fusion [ALIF], extreme lateral interbody fusion, transforaminal lumbar interbody fusion) or posterior decompressions and fusion in which the interspinous processes are left intact.

103.5 Contraindications

103.5.1 Interspinous Motion-Preservation Devices

All of the posterior interspinous process devices share many of the same contraindications. Any patient whose spinal anatomy could result in an unstable device placement should not undergo device implantation. Specific conditions include isthmic/unstable spondylolysis, unstable spondylolisthesis (> grade I), neoplasm, fracture of the spinous process or pars interarticularis, and idiopathic scoliosis. Relative contraindications include osteoporotic bone and stable degenerative spondylolisthesis (grade I). Because of the anatomy of the S1 spinous process, interspinous motion preserving implants are not currently recommended for use at L5–S1.

103.5.2 Interspinous Fusion Devices

The contraindications for IFD placement are the same as for IMPDs. Because IFDs require fixation to intact posterior elements, they are not indicated in posterior lumbar interbody fusions or decompressions that involve bilateral laminectomy. Additionally, IFDs are not intended for stand-alone use as there is risk of spinous process fracture.

103.6 Special Considerations

Preoperative imaging is essential to determine the etiologic and anatomical sites of neural compression. Plain radiographs, in addition to magnetic resonance imaging (MRI), and/or myelography and postmyelogram computed tomography (CT) imaging are essential for identifying sites of neural compression.

103.7 Special Instructions, Positioning, and Anesthesia

Traditional fusion procedures disrupt the normal segmental musculature and the inherent dynamic stabilization of the spine likely degrading the surgical outcome. As such, certain devices such as the DIAM or coflex conform to the interspinous anatomy and allow placement with minimal disturbance of the segmental muscles through a simple midline approach with preservation of the segmental anatomy. The patient is placed in the standard prone position or the lateral decubitus position. When an IFD is utilized in conjunction with an ALIF, the patient is repositioned prone after the interbody spacer placement. Stand-alone IMPDs may be placed under general or local anesthesia as an outpatient procedure.

103.8 Tips, Pearls, and Lessons Learned

Interspinous motion-preservation devices and IFDs utilize a similar surgical approach; therefore, in this chapter we discuss techniques for the X-Stop that may also be applied to other implants. Surgical techniques vary slightly between individual devices. The most frequently involved anatomical level is L4–L5. The surgical approach is performed using a standard midline incision or a slightly lateral incision (10 mm lateral to the midline). The fascia is incised to the right of the supraspinous ligament. A counterincision is necessary for insertion, preparation, and seating of the device. Unless the implant design calls for resection of the supraspinous ligaments, care must be taken to maintain continuity of the supraspinous ligament by preserving a band at least 10 mm wide and as thick as possible. Preservation of the supraspinous ligament prevents posterior migration of the implant. A window is created in the interspinous space using a scalpel that is ideally curved upwards; the window is then enlarged with a dilator or curved Kerrison taking care to preserve cortical bone (▶ Fig. 103.1). At this stage, the interlaminar sizer/distractor is inserted as far anteriorly as possible at the junction between the base of the spinous process and the laminae (▶ Fig. 103.2). Proper fit of the interspinous prosthesis should be based upon retensioning of the supraspinous

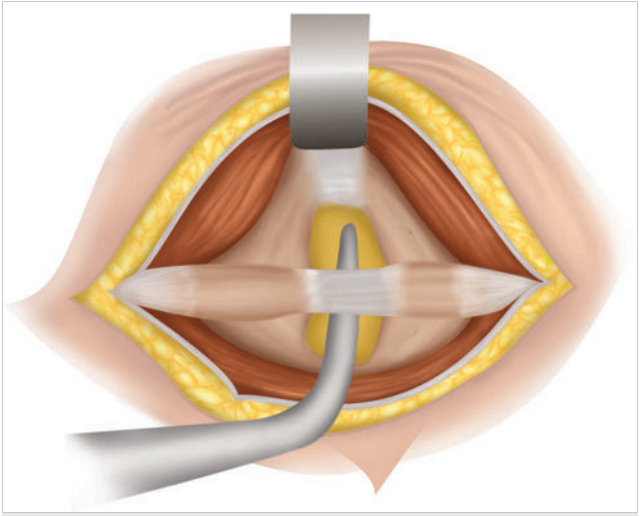

Fig. 103.1 Resection of the interspinous ligament down to the ligamentum flavum creating a window in the interspinous space.

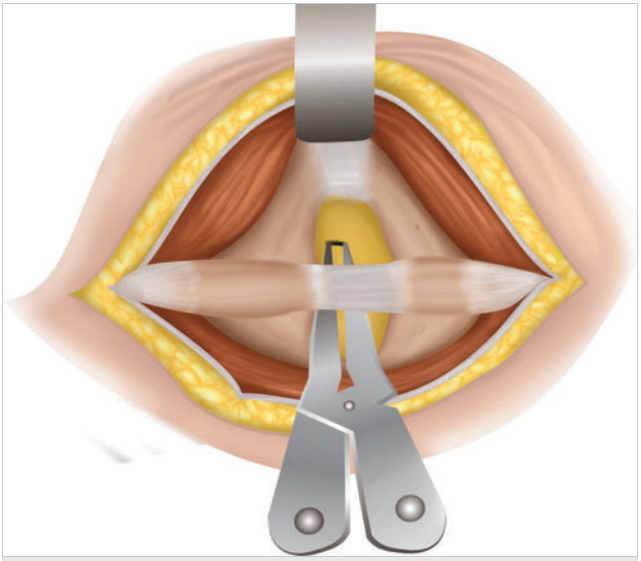

Fig. 103.2 Placement of the interspinous distractor and sizer.

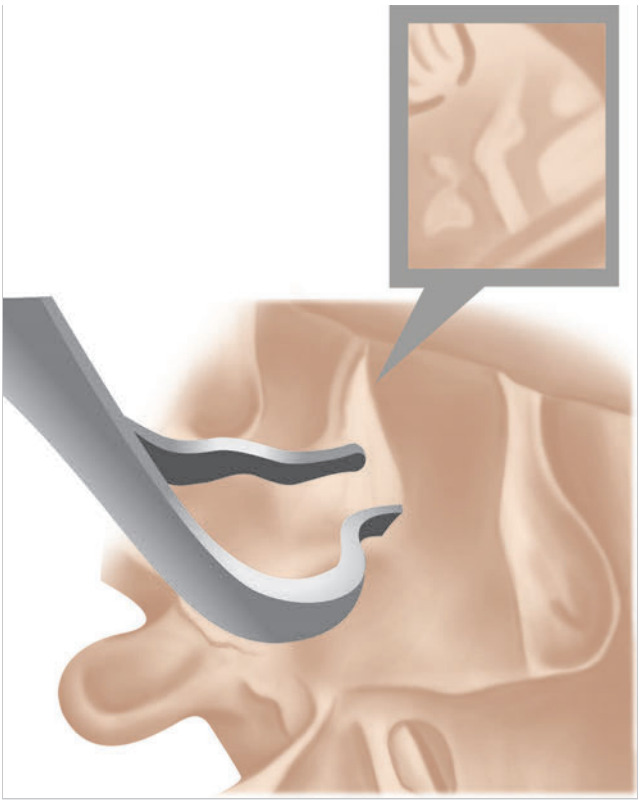

Fig. 103.3 Gentle distraction is applied between interspinous processes to appropriately tension the interspinous ligaments.

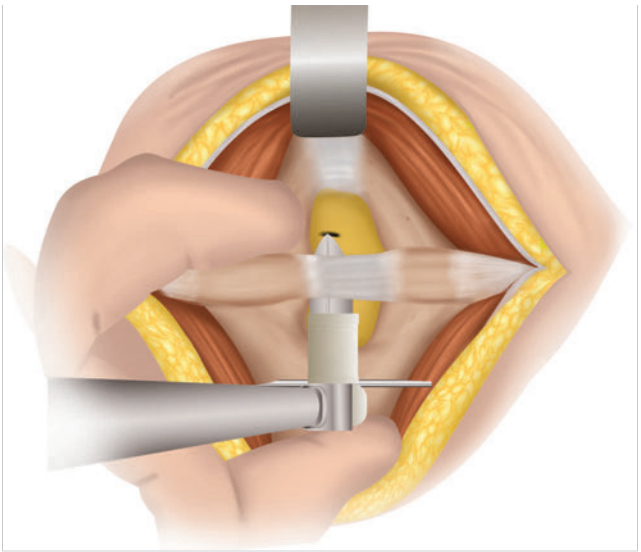

Fig. 103.4 The interspinous implant is positioned anteriorly and slid between spinous processes.

ligament and/or realignment of the facets and articular capsule (▶ Fig. 103.3). Parallel alignment of the end plates can also be used as a reference for retensioning of the posterior longitudinal ligament. The implant is placed between the spinous processes (▶ Fig. 103.4). The impactor is placed on top of the implant and the prosthesis is pushed down with gentle taps of the mallet. The opposite wing is attached to the spacer assembly so that the two wings straddle the spinous processes above and below (▶ Fig. 103.5, ▶ Fig. 103.6).

103.9 Difficulties Encountered

Caution is required not to violate the supraspinous ligament when creating the window in the interspinous space. When distracting the spinous processes, using excessive force may result in a fracture of the spinous process. In cases of overlapping and hypertrophic laminae (kissing laminae) trimming is recommended. Similarly, in cases of a kissing spine involving the spinous processes, trimming of the lateral hypertrophic aspects of the spinous process is necessary.

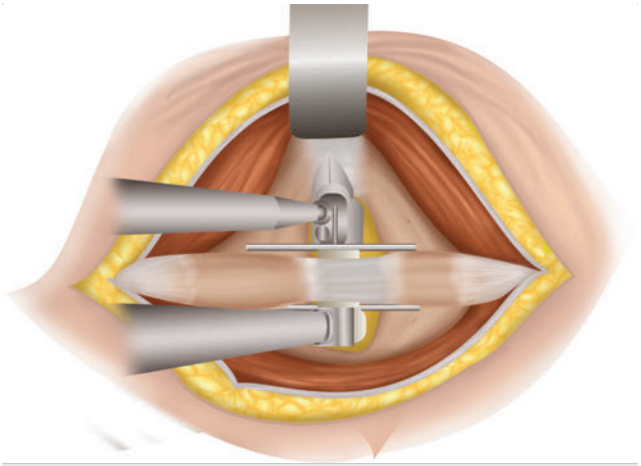

Fig. 103.5 The opposite lateral wing is secured completing the device assembly.

103.10 Key Procedural Steps

- Localizing lateral radiograph
- Soft-tissue dissection with preservation of the midline spinal structures
- Counterincision necessary for insertion, preparation, and seating of the device
- Neurologic decompression limited to sites of anatomical decompression identified on preoperative imaging studies
- Resection of the interspinous ligament down to the ligamentum flavum creating a window in the interspinous space (▶ Fig. 103.1)
- Placement of the interspinous distractor as far anteriorly as possible (▶ Fig. 103.2)
- Implant selection and prosthesis trial sizing (▶ Fig. 103.3)
- Final positioning using the impactor (▶ Fig. 103.4)
- Implant fixation to the adjacent spinous processes (▶ Fig. 103.5)

103.11 Bailout, Rescue, and Salvage Procedures

Excessive interspinous ligament resection and spinous fracture may render the interspinous implant unusable. A standard decompression should be performed with spinal fusion implemented if the motion segment is deemed to be unstable.

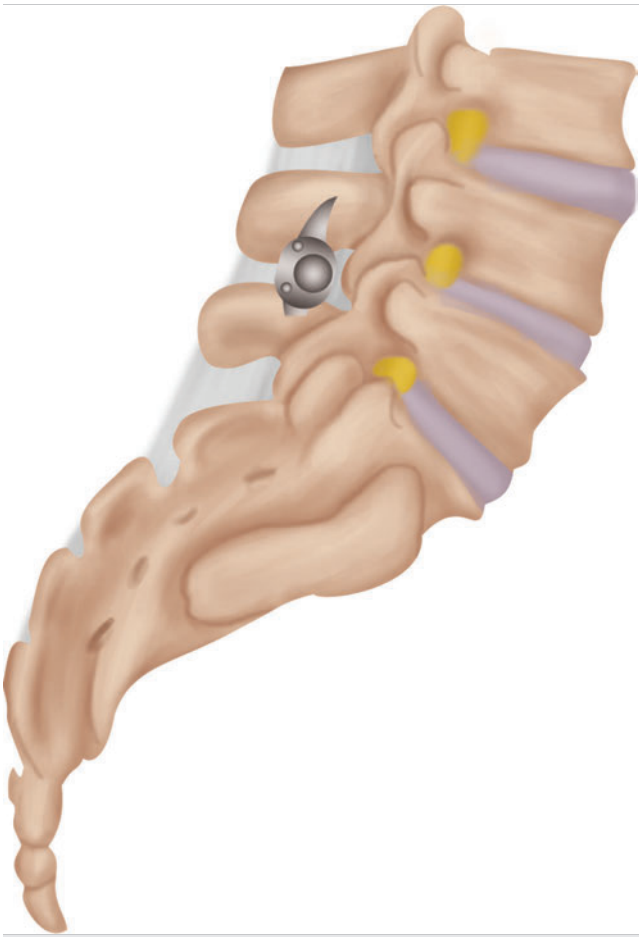

Fig. 103.6 Lateral view of the X-Stop device situated between spinous processes with lateral wings straddling the spinous processes above and below.

Pitfalls

- Care must be taken to maintain continuity of the supraspinous ligament by preserving a band at least 10 mm wide and as thick as possible.
- Excessive spinous process resection and undue force with the distractor may result in a fracture of the spinous process causing segmental spinal instability.
- Excessive distraction and oversized prosthetic implantation may result in creation of localized kyphosis and increased pressure on the disk accelerating spinal degeneration.

104 Cervical Disk Replacement

Justin W. Miller and Rick C. Sasso

104.1 Description

Anterior cervical diskectomy and fusion (ACDF) is the gold standard for treating patients with cervical radiculopathy or myelopathy refractory to nonoperative measures. The safety and effectiveness of this procedure have been established and clearly demonstrated in the literature; however, potential limitations with ACDF exist, and new alternatives including disk arthroplasty are now available with promising results. Such innovative technology attempts to address kinematic and biomechanical factors in cervical spine motion. Intervertebral disk replacement is designed to preserve motion, both at the affected and adjacent levels, and avoid limitations of fusion. Adjacent level degeneration may be seen in patients having undergone cervical fusion at a rate of 2.9% annually. Such new-onset degenerative changes and possible recurring neurologic symptoms may be delayed or eliminated with cervical disk replacement. In addition, potential complications related to fusion such as pseudarthrosis, anterior plate problems, and morbidity associated with bone graft harvest may be avoided. Cervical disk arthroplasty is designed to provide physiologic motion and eliminate abnormal stresses at adjacent levels that may lead to accelerated degeneration.

104.2 Key Principles

- Cervical disk arthroplasty is a viable alternative to ACDF.
- Patient selection is important.
- Preparation and insertion of a disk arthroplasty device is technically demanding and requires proper experience/training.
- Outcome measures thus far show equivalent or superior results compared to ACDF.

104.3 Expectations

Disk arthroplasty results may be highly subject to surgeon technique. Preoperative planning with magnetic resonance imaging (MRI) or computed tomography (CT) myelogram is essential to determine neural compressive lesions. Appropriate disk sizing and assessment of osteophytes is performed with preoperative imaging. Disk height should be relatively normal without profound collapse; facet joints should not be arthritic; and reasonable motion should be present. Appropriate end-plate preparation is critical to allow for bony ingrowth into the prosthetic shell while maintaining the strong subchondral end plate. Undersizing the base-plate area may result in end plate damage and implant subsidence. Prosthetic disk placement is confirmed with fluoroscopy. Postoperative immobilization is not necessary.

104.4 Indications

Intervertebral disk replacement is indicated for cervical radiculopathy due to a herniated disk or osteophyte complex at one or two levels between C3 and C7 (▶ Fig. 104.1). Single-level focal pathology resulting in myelopathy is also a possible indication. With the exception of myelopathy, patients must have failed aggressive nonoperative treatment modalities and be skeletally mature with relatively normal segmental motion.

104.5 Contraindications

Cervical disk replacement should not be performed in patients with sagittal plane abnormalities, spondylolisthesis, retrolisthesis, spondylolysis, or any evidence of segmental instability. Patients with significant medical comorbidities and those with active infections are excluded. Patients with a history of previous cervical surgery, metabolic bone disease, progressive neuromuscular disease, significant osteoporosis, or those on corticosteroid therapy, are also poor candidates. Patients with radiographically confirmed ankylosis, ossification of the posterior longitudinal ligament, kyphosis, end-plate abnormalities, or facet joint arthroses should be excluded. Treatment of cervical myelopathy secondary to factors other than a soft disk herniation at a single level should be avoided.

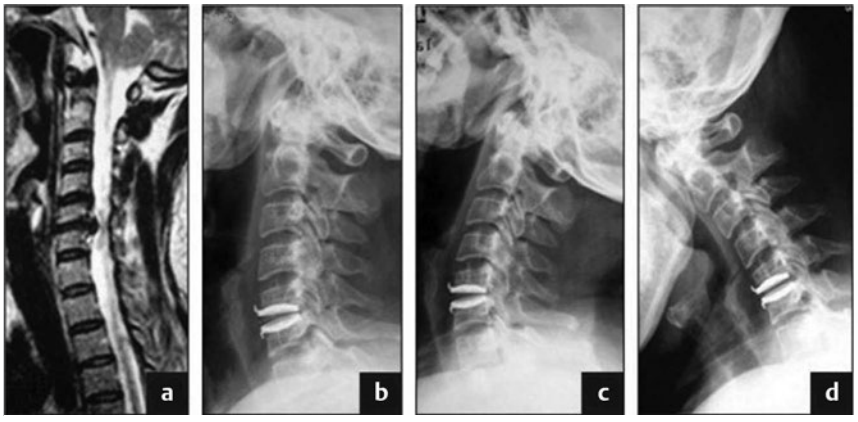

Fig. 104.1 **(a)** Single level disk herniation with remainder of cervical region normal. **(b-d)** Neutral, extension, and flexion views following arthroplasty placement.

Fig. 104.2 Current disk arthroplasty devices approved by the Food and Drug Administration.

104.6 Special Considerations

There are numerous disk arthroplasty systems (▶ Fig. 104.2) for which early and short-term data have been reported, but longer-term outcomes are still needed. Several meta-analyses have been performed pooling current data available from randomized controlled studies and showing either equivalent or superior results with arthroplasty compared to fusion for most outcome measures. The clinical benefits of maintaining motion and providing symptom relief are postulated to delay or avoid adjacent-level degeneration: Data regarding this benefit are lacking and longer follow-up is warranted. Although not considered the current gold standard, wide acceptance will depend on long-term outcome studies. Current success with artificial cervical disk replacement has demonstrated that the intended effects are indeed being achieved (i.e., sparing cervical motion and improving outcomes).

104.7 Special Instructions, Positioning, and Anesthesia

Patient positioning is supine on a standard operating table, with the spine stabilized in the neutral sagittal alignment. Extra care is taken to avoid any flexion or extension as this can impact proper preparation for the arthroplasty. It is important to perform adequate decompression of both the spinal canal and bilateral neuroforamen. With motion-sparing techniques, you must decompress all neurologic elements, including the asymptomatic side, to prevent new or recurrent problems in the future. Standard anesthetic techniques are used during this procedure.

104.8 Tips, Pearls, and Lessons Learned

Important considerations for a good outcome include adhering to strict patient selection, careful preoperative planning, and meticulous surgical technique. One of the most important lessons learned is the importance of complete neural decompression when motion-sparing devices are implanted. Neural tissue is protected in a fused nonmobile setting; however, neural tissue is placed at risk in a mobile segment, especially if the motion is increased and residual compressive disk tissue or osteophytes remain. Future symptoms can develop if relative stenosis present on the asymptomatic side is not addressed during the index surgery. Radicular symptoms may begin postoperatively on what was initially the asymptomatic side as increased motion commences.

104.9 Difficulties Encountered

- Incorrect patient positioning can result in improper insertion of the implant.
- Failure to adequately decompress the neural elements can result in future symptoms.
- Inadequate removal of osteophytes/lateral decompression can complicate implant sizing and milling.
- Over- or undersizing of the implant can result in complications.

104.10 Key Procedural Steps (Video 104.1)

- Intraoperative positioning in the neutral sagittal alignment (avoid hyperextension or flexion)
- Complete diskectomy with complete neural decompression
- Verification of midline
- Preparation of end plates
- Insertion of device
- Radiographic verification of position

104.11 Bailout, Rescue, and Salvage Procedures

Most cervical disk replacements can be repositioned intraoperatively if acceptable placement is not initially achieved. Those devices that achieve initial stability with a keel that is cut into the vertebral body may be difficult to realign. The ultimate bailout, rescue, and salvage procedure for a cervical disk replacement is a standard anterior cervical fusion with instrumentation.

Pitfalls

- Malplacement of the artificial disk implant can result in a neurologic deficit or later malfunction of the disk. It is imperative that the cervical disk replacement implant be well positioned. This is much more critical than positioning of a bone graft for fusion.
- Early postoperative pitfalls include recurrent laryngeal nerve palsy, dysphagia, and implant migration. Late pitfalls may include heterotopic ossification, implant loosening, and juxtalevel changes.

105 Lumbar Spinal Arthroplasty

Scott L. Blumenthal and Jeffrey L. Biehn

105.1 Description

Spinal fusion for symptomatic degenerative disk disease unresponsive to nonoperative care has been regarded as the gold standard. However, it has the potential for pseudarthrosis. Fusion may also accelerate adjacent segment degeneration due to the relatively rigid fusion segment increasing the stresses at the adjacent level(s). These issues have highlighted the need for a surgical treatment that spares spinal motion, allowing motion to be closer to that of pre-illness levels and to allow a more rapid return to work and other activities by not having to wait for the solid fusion to incorporate.

105.2 Key Principles

Disk replacement should not be considered in patients with fracture, infection, spondylolisthesis, spinal stenosis, sacroiliac problems, or facet-related pain. These diagnoses should be ruled out as the primary pain source. History and physical examination followed by anteroposterior (AP) and lateral flexion and extension radiographs should be performed. Magnetic resonance imaging (MRI) is a helpful study to evaluate the intervertebral disks, spinal canal, and neural foramen. One must be cautious in assuming that every degenerated "black disk" found on MRI is a source of pain. We have found it helpful to perform diskography to evaluate intradiskal injection pressure and volume, disk morphology, and most importantly, reproduction of the patient's usual pain during the disk injection. Pain intensity during injection can be assessed on a 0 to 10 scale at each level. The patient should be awake and blinded to the level being tested. Facet pain may be ruled out by history and physical examination. If in doubt, a facet injection may be performed. Bone densitometry should be obtained for all patients being considered for a spinal arthroplasty procedure, especially if there is any concern about their bone quality or if their history indicates a high risk of osteoporosis.

105.3 Expectations

Pain arising from degenerative disk disease at one or more lumbar levels not responding to nonoperative measures is the primary indication for spinal arthroplasty. The goals of spinal arthroplasty are to maintain motion, relieve pain, preserve disk space height, maintain neural foraminal height, and preserve the facet joints. It is important to have longevity of any implant through millions of cycles and to aim for avoidance of revision surgery. This requires excellent wear characteristics of any spacer, good shock-absorbing capacity, and a solid interface between the device and the host bone without sacrificing revision options. The expectation of the surgical procedure is that patients experience significant relief of their back pain and are able to resume activities of daily living as well as some recreational activities or preinjury occupation.

105.4 Indications

The primary candidate for total disk replacement (TDR) is a patient with degenerative disk disease with no more than grade 1 spondylolisthesis at the involved level with no significant facet changes and who has failed at least 6 months of nonoperative care. Patients with radicular pain in addition to axial pain can be treated with artificial disk replacement as long as severe central or foraminal stenosis does not exist. Loss of disk height is corrected with distraction during insertion of the artificial disk. Thus, indirect decompression of mild to moderate foraminal stenosis is accomplished with restoration of disk height.

Typically, patients are younger than 60 years of age. It is critical the patient is evaluated for instability as well as bone quality. Bone-mineral-density value of one standard deviation below normal population (T score < -1.0) or less as determined by dual energy X-ray absorptiometry (DXA) is a contraindication for disk replacement.

105.5 Contraindications

The presence of infection, fracture, or disruption of posterior structures or instability from a pars defect or pedicle fracture should be regarded as absolute contraindications. The level to be treated should not have greater than a grade I spondylolisthesis. The presence of a rigid deformity is a contraindication. In addition, patients with allergies or sensitivities to arthroplasty implant materials such as cobalt, chromium, molybdenum, polyethylene, tantalum, and titanium are also contraindicated.

105.6 Special Considerations

Most artificial disk devices consist of a metal end plate that anchors into the vertebral end plate (▶ Fig. 105.1). These metal end plates articulate with a spacer (▶ Fig. 105.2), which allows motion at the segment. The metal end plates are available in different cross-sectional sizes and lordotic angles, and come with or without a porous coating and have either teeth or keels to gain stability into the bony vertebral end plate. The spacers come in various thicknesses and consist of either metal or polyethylene. The TDR devices have varying levels of constraint. Another type of implant is a one-piece device with a compressible core between end plates.

105.7 Special Instructions, Positioning, and Anesthesia

The help of an access surgeon is strongly advised. A rolled towel may be placed under the patient's lumbar spine to help local lordosis and assist in disk tissue removal and implantation of the device. The towel may later be removed on device insertion. Similarly, the table can be re-flexed and flexed to open up the disk space when desired. Be sure the desired level is at the "break" in the table. Often it is necessary to release the

posterior longitudinal ligament to allow adequate mobilization. This can be accomplished with curettes or specialized distracters and paddles.

105.8 Tips, Pearls, and Lessons Learned

The results of a 5-year follow-up of several TDR devices undergoing evaluation in Food and Drug Administration-regulated clinical trials have been published and/or presented at professional conferences. The findings indicate these devices produce results similar or superior to fusion and outcomes were stable during the course of the study. There was a greater rate of adjacent-level degeneration in the fusion group compared with TDR (28.6% vs. 9.2%). Additionally, range of motion remained unchanged compared with the previous 2-year follow-up study results.

Long-term follow-up studies of TDR patients have been published in Europe where TDR has been performed since the mid-1980s. A study with a minimum 10-year follow-up for 100 patients found that 62% of patients had an excellent outcome, with an additional 28% indicating a good outcome. The return to work rate was 91%. Five patients (5%) required a secondary posterior fusion. There was no indication of significant problems with the durability of the devices long term.

Fig. 105.1 The implant as it should be positioned at the midline of the vertebral body. (© 2013 Synthes, Inc. Reproduced with permission.)

105.9 Difficulties Encountered

Because an anterior approach is required, the presence of vessel calcification, which may be seen on lateral radiographs, should be evaluated with computed tomography. If circumferential calcification is present, it is often inadvisable to proceed except at the L5–S1 level, where the vessels need minimal retraction. A vascular opinion can be sought in cases of uncertainty.

105.10 Key Procedural Steps

A direct anterior approach is used with a transverse incision for a one-level replacement depending on body habitus or a vertical incision for multilevel procedures. A retroperitoneal approach is preferred, but a transperitoneal approach may also be used. Care must be taken to preserve sympathetic and parasympathetic nerves to avoid erectile dysfunction and retrograde ejaculation in the male patient. It is also important to avoid lymphatic structures and to protect all vascular structures at all times.

It is important to obtain wide exposure of the disk space and perform a total diskectomy, while being careful to avoid damaging the end plates. Intact end plates are important for obtaining good fixation and avoiding subsidence. To avoid lateral tilt, care must be taken to restore the appropriate lordosis and obtain adequate end-plate coverage. The spacer insert must be of the appropriate thickness to allow a snug fit without overdistracting the disk space. When working above the L5–S1 level, it may be necessary to allow the vessels to relax from time to time to allow some blood flow into the left leg. The vessels and distal pulses should be palpated at the end of the surgery to ensure no vascular insult. A pulse oximeter applied to the great toe during retraction of the vessels can provide valuable information concerning lower extremity circulation intraoperatively.

It is important to place the device as close to the true midline as possible and as far posterior as possible without breaching the spinal canal (▶ Fig. 105.3). Intraoperative fluoroscopy is necessary for precise alignment in the sagittal and coronal planes (▶ Fig. 105.4).

105.10.1 Postoperative Protocol

All patients may be weight-bearing immediately after surgery and are encouraged to stand and ambulate with a therapist the day of surgery. Standing X-rays are obtained the morning after surgery to document the position and rule out migration in the weight-bearing position. Patient-controlled analgesia is used on the first postoperative night for pain control. Compression

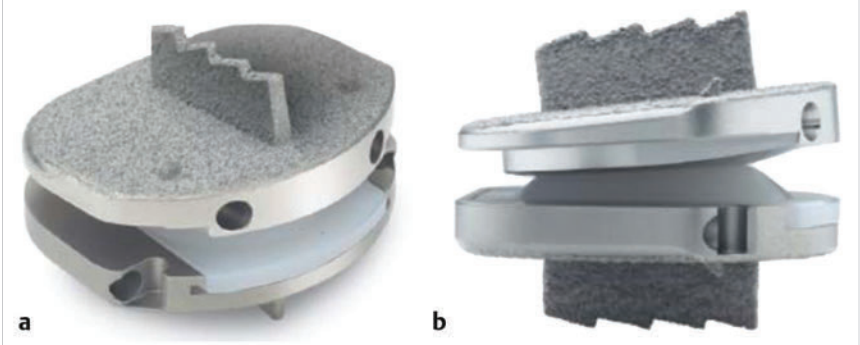

Fig. 105.2 **(a)** The fully assembled prosthesis as it would sit in vivo. The polyethylene core can be seen inserted onto the lower device end plate. (**b**) Lateral view of the device. (© 2013 Synthes, Inc. Reproduced with permission).

Fig. 105.3 A properly positioned implant. Note the posterior placement, but with no penetration of the canal at the posterior aspect of the superior end plate of L5. (© 2013 Synthes, Inc. Reproduced with permission.)

stockings and sequential foot or leg pumps are also used on the first postoperative night. Most single-level patients go home the following morning. Patients are advised to avoid extension, stooping, excessive twisting, or any heavy lifting the first 6 weeks, and may then gradually resume normal activities. Participation in extreme or contact sports is not encouraged.

105.11 Bailout, Rescue, and Salvage Procedures

Revision options include avoiding the entire anterior implantation area completely and performing a posterior fusion. If removal of the device is indicated, it may be replaced with a new TDR, or an anterior fusion may be performed with or without a supplemental posterior construct. The approach for removing the primary TDR prosthesis may be done through a repeat direct anterior approach or through a lateral approach, avoiding the area of scar tissue.

Pitfalls

Potential complications of disk replacement include

- Subsidence
- Device dislocation and migration
- Radicular pain, weakness, dysesthesia
- Infection
- Polyethylene wear, osteolysis, and loosening
- Metal debris and oncogenic potential (no clinical cases identified)
- Acceleration of facet joint arthrosis
- Instability (too thin of a spacer)
- Postoperative scoliosis (poor device positioning)

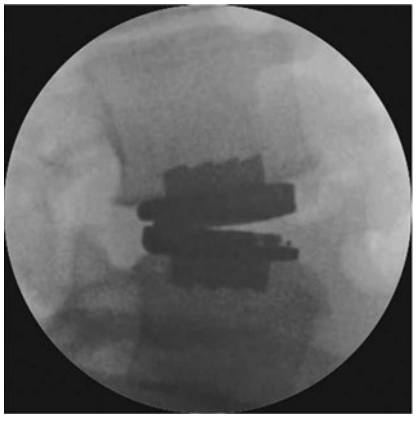

Fig. 105.4 Intraoperative fluoroscopic images demonstrating proper implant positioning.

106 Lateral Lumbar Spinal Arthroplasty

Carlos Castro, Luis Marchi, Leonardo Oliveira, Thiago Coutinho, Thabata Bueno, Luiz Pimenta, and Alexander R. Vaccaro

106.1 Description

There are a variety of ways to perform an anterior lumbar interbody fusion. One may choose the standard anterior retroperitoneal approach, transperitoneal approach, or the lateral approach.

106.2 Key Principles

Lumbar interbody fusion involves the placement of a structural implant (spacer, allograft, or cage) within the disk space after a complete diskectomy and preparation of the end plates (▶ Fig. 106.1). Patients treated with fusion generally experience reduced back pain and improved function. The potential for increased rates of adjacent segment disease after fusion has motivated the development of arthroplasty devices (total disk replacement [TDR]) that are intended to provide continued motion while at the same time minimizing stresses at adjacent levels.

106.3 Expectations

To date, most lumbar TDR surgery has been performed via the anterior retroperitoneal and rarely the transperitoneal approach. The anterior approach to the placement of lumbar TDR devices has inherent limitations, including considerable collateral damage to surrounding tissues and risk of vascular and visceral injuries. Complications include sympathetic dysfunction, vascular injury, somatic neural injury, sexual dysfunction, prolonged ileus, deep vein thrombosis, acute pancreatitis, and bowel injury. Studies of anterior TDR surgeries have reported similar approach-related complications.

By approaching the spine laterally, many of these potential risks can be reduced or avoided. Besides that, placement of a TDR device from the lateral approach is thought to allow for easier, less-invasive access to the disk space, preservation of stabilizing ligaments such as the anterior longitudinal ligament (ALL), greater end plate support, and the opportunity for safer revision surgery.

106.4 Indications

The indications for lateral TDR are similar to the indications for anteriorly placed TDR devices—in general, degenerative disk disease without facet degeneration that has failed a structured nonoperative treatment regimen for at least 6 months. Imaging studies such as dynamic plain X-rays must exclude instability, and degeneration is supported by magnetic resonance imaging (MRI). Further support for a symptomatic level (s) may also be provided by provocative diskography. A lateral disk replacement can only be inserted at the L1–L2, L2–L3, L3–L4, or L4–L5 levels.

106.5 Contraindications

- Prior lumbar fusion surgery at the operative level
- Prior lumbar laminectomy at the operative level
- Prior complete lumbar facetectomy at the operative level
- Prior bilateral retroperitoneal surgery
- Radiographic signs of significant instability at operative level (≥ 3-mm translation, ≥ 11 degrees angulation compared to the adjacent level)
- Bridging osteophytes or absence of motion ≤ 2 degrees
- Radiographic confirmation of significant facet joint disease or degeneration
- Pars defect, facet abnormality, or another compromise of the posterior elements
- Spondylolisthesis (> grade 1)
- Osteopenia, osteoporosis, or osteomalacia
- Active local or systemic infection

106.6 Special Considerations

The midline markers on the prosthesis should align with the lateral center of the vertebral bodies in a lateral fluoroscopic view. Lateral insertion of the device in the midline provides ideal placement and rotation because the kinematic center of rotation is located posteriorly within the device.

The ALL provides an anterior restraint not only to extension, but also to axial rotation. It has been shown that resection of the ALL leads to hypermobility of the segment and potential

Fig. 106.1 Case example of lateral disk replacement showing preoperative magnetic resonance image (left) and 12-month follow-up images.

Fig. 106.2 Case example of lateral disk revision showing 24-month follow-up images (left) and postextreme lateral interbody fusion images.

facet arthrosis at the same level and adjacent levels. Lateral device insertion leads to tensioning of the ALL and posterior longitudinal ligament (PLL) and remaining anulus. A well-placed lateral TDR has less motion than an intact spine and is more controlled with a more natural neutral zone.

106.7 Special Instructions, Positioning, and Anesthesia

It is important to properly position the patient in the lateral decubitus position. Use of intraoperative hand-held and dynamic electromyography (EMG) is used to assist in avoiding injury to the lumbar plexus. Ipsilateral and contralateral anulus release provides cortical bone support to the interbody prosthesis along the apophyseal ring to prevent device subsidence.

106.8 Tips, Pearls, and Lessons Learned

The lateral approach to arthroplasty placement has been shown to restore disk height and indirectly decompress the neural structures by ligamentotaxis along with improving sagittal balance. Range of motion (ROM) has been shown to be maintained up to 36 months in comparison with preoperative values.

106.9 Difficulties Encountered

Contralateral disk space-level bone formation may be seen following arthroplasty placement over time. However, this may not effect clinical results or mean ROM (▶ Fig. 106.2). A real concern with the lateral approach is the risk of injury to the nerves of the lumbar plexus within the psoas muscle. This highlights the benefits of real-time, stimulus-evoked EMG essential in identifying nerves during the approach. In a standard retroperitoneal approach, a revision procedure, particularly after the first 2 weeks postoperatively due to scar formation, presents an elevated risk of vascular injury, especially at the level of the vascular bifurcation at L4–L5. Use of the lateral approach does not require anterior mobilization of the major vessels to revise an anteriorly placed TDR device.

106.10 Key Procedural Steps

Video 106.1 shows a surgical procedure for the implantation of a TDR by the lateral approach. The approach technique does not differ significantly from the standard lateral approach for fusion procedures, with the added distinction that the exposure required for TDR device placement must extend more posteriorly than the exposure for a fusion procedure, making real-time stimulated EMG monitoring an especially important part of this procedure. Once the lateral aspect of the disk space is exposed, an anulotomy is created. Then, a standard diskectomy and end plate preparation are performed, always while maintaining the integrity of both the ALL and PLL. A complete and thorough diskectomy must be performed to the contralateral margin, and the contralateral anulus is then released. This ensures parallel distraction and proper coronal alignment and permits the placement of the device in its ideal position on both sides of the ring apophysis.

Following sequential sizing of the device using trials, the lateral TDR device is inserted as a single assembly. The device consists of a superior end plate and an inferior end plate that mate to each other by means of a metal-on-metal (cobalt-chromium-molybdenum alloy) ball-and-socket articulation (▶ Fig. 106.3). The bone-contacting surfaces of the end plates have spikes to facilitate short-term fixation into the vertebral bone and are also coated with a dual-layer titanium plasma spray and hydroxyapatite plasma spray to facilitate bone in-growth for long-term fixation. The device, which provides surface area coverage of > 50% of the end-plate area (▶ Fig. 106.4), should span the ring apophysis on both sides for strong end plate support.

106.11 Bailout, Rescue, and Salvage Procedures

Primary placement of a lumbar TDR device from a lateral approach appears to be safer to revise should removal and revision be necessary. Not only can the contralateral retroperitoneal approach be performed easily, but because the primary procedure does not create scar formation in or around the anterior vasculature, an anterior approach (either trans- or retroperitoneal) can be performed more safely (▶ Fig. 106.5).

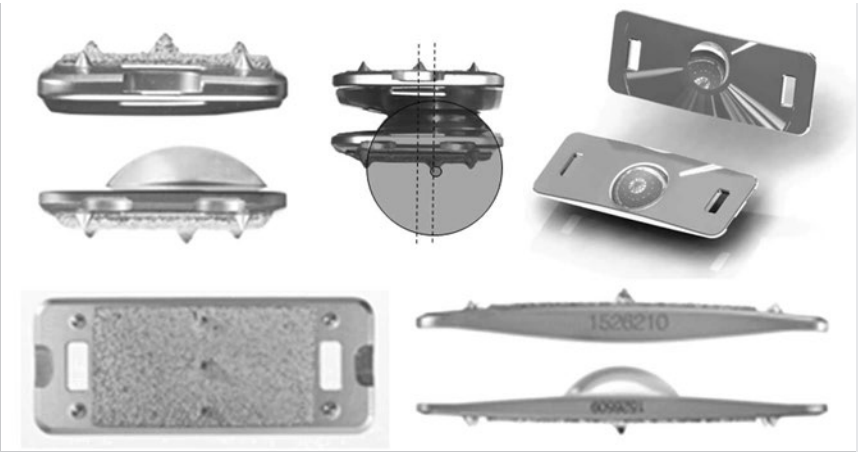

Fig. 106.3 Photograph showing the XL total disk-replacement device—a metal-on-metal, ball-in-socket articulation with a dual-layer titanium plasma spray and hydroxyapatite plasma spray coating.

Fig. 106.4 **(a)** Axial, (**b**) sagittal, and (**c**) coronal computed tomography images of the XL total disk-replacement device seated across the ring apophyses of the L4–L5 disk space, with significant end-plate area coverage.

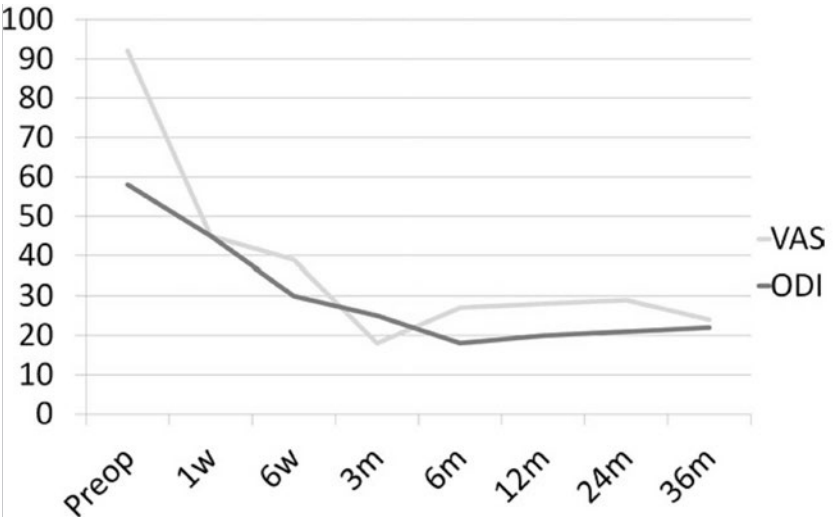

Fig. 106.5 Clinical outcomes up to 36 months. Postoperative scores were statistically significantly better ($P < 0.05$). ODI, Oswestry Disability Index; VAS, visual analog scale.

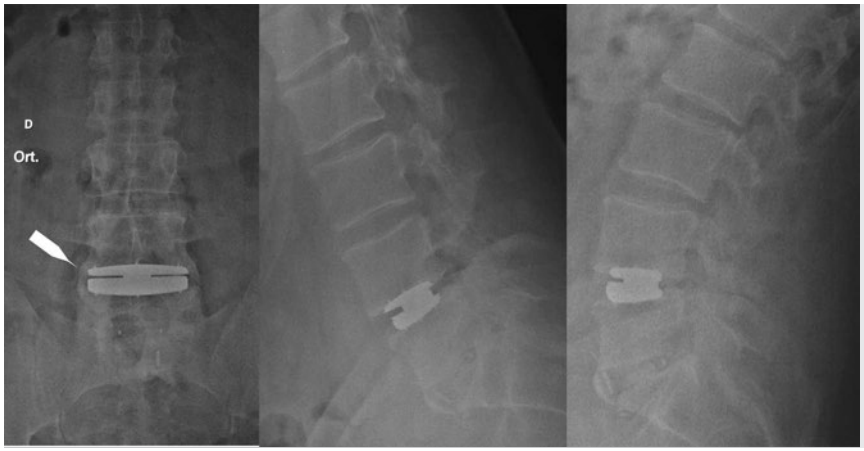

Fig. 106.6 Case example of grade IV heterotopic ossification. Contralateral bone formation is shown by the arrow. Fusion at the index level is evidenced by the dynamic X-rays.

Pitfalls

- A prominent complication described in the literature regarding TDR is heterotopic ossification. The presence of heterotopic bone formation has been seen on the contralateral side of device placement with the lateral approach. This finding has not been correlated with worsened clinical outcomes (▶ Fig. 106.6).
- Previous reports have shown that the ALL is an important retainer in extension and axial rotation and that its resection leads to hypermobility and facet arthrosis at the same level and adjacent levels. The maintenance of the ALL, preserved by a laterally placed TDR, generates a biomechanical environment that prevents anterior displacement and excessive loading of the facet joints, improving ligamentotaxis and sagittal balance, which leads to a more natural neutral zone and a more constrained movement of the lumbar spine.

Section XXI

Complications Management

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XXI

107 Posterior Revision Strategies for Dura and Nerve Root Exposure following a Previous Laminectomy

Tristan Fried, Caleb Behrend, Erik Spayde, and Alexander R. Vaccaro

107.1 Description

Revision surgery is associated with increased risk of poorer patient outcomes and higher rates of complications. A clear understanding of the patient's goals in treatment, the prior surgical history, and current anatomy as altered by the preceding procedures is critical for developing a safe surgical plan. The importance of a safe and effective plan cannot be overstated for these revision procedures.

107.2 Expectations

Patients having undergone surgery have increased probability of intraoperative complications and some postoperative complications including infection and non-union. In addition, many have suffered chronic pain, failure of prior operations, or have already dealt with complications. The surgical plan must be drafted with a clear understanding between patient and surgeon of the goals of treatment and a discussion of the increased risks associated with revision surgery. Preparation begins with an in-depth history, physical exam, acquisition of prior surgical records, and complete imaging studies. Managing patient expectations is critical in aligning the goals of both the surgeon and the patient. Revision procedures are less standard and less predictable than the original procedure. Some of the specific challenges of revision surgery include increased risk for dural tear, increased blood loss, infection, complications associated with increased operative time, prolonged rehabilitation time, and a greater risk for persistence of symptoms.

107.3 Indications

Common indications for revision surgery include pain, weakness, claudication, or imbalance. These problems can occur following prior surgery and are often related to spinal instability, deformity, recurrent disk herniation, adjacent level disease, pseudarthrosis, technical errors related to the previous surgery, or infection.

107.4 Contraindications

Contraindications can be grouped by general health considerations, approach related, and those arising from the spinal pathology itself. One must keep an open mind to look at all treatment options and operative approaches. When presentation makes the surgical revision an elective surgery, significant medical comorbidities, active nonspinal infection, uncorrected anticoagulation, and insufficient trial of nonoperative intervention could be a considered contraindications to surgery. In this setting, pregnancy also can be a reason to delay a surgical case. In many cases, surgery is not contraindicated, but a specific approach may be contraindicated, such as anterior cervical revision in the setting of unilateral vocal cord paresis. In this case, a posterior approach or ipsilateral revision anterior exposure is indicated. This specific example illustrates the importance of understanding the prior surgical history. This injury may occur not only after anterior cervical diskectomy and fusion procedures, but numerous otolaryngologic, plastic, and other interventions. Anterior exposures to the thoracolumbar spine also have dramatically increased risk in the setting of some prior abdominal surgical procedures, retroperitoneal fibrosis, or prior vascular interventions. Although not an absolute contraindication, alternative approaches should be considered.

Other contraindications may be more versed. For example, in the case of a lateral disk herniation or a recurrent or multiple recurrent disks at a given level, a transforaminal lumbar interbody fusion procedure could be considered as an alternative. At other times, a posterior approach may be avoided altogether such as when approaching a recurrent disk at a level with a conjoined nerve root. In this scenario, root retraction is fraught with potential complications; therefore, an anterior or lateral diskectomy and decompression may be a reasonable approach.

107.5 Special Considerations

The importance of acquisition of surgical records and detailed medical history cannot be overstated. A patient who has had inadequate initial surgical decompression or who develops acquired stenosis or instability, deformity, or infection has a high probability of benefiting from revision surgery. Timing of revision may contribute to the technical challenges encountered intraoperatively. Surgery performed within one month will not have the same mature scar and adhesion formation of older surgeries. Surgical decompression performed years later will likely have prominent scar adhesions, as well as further acquired degenerative bony changes.

Plain radiographs in the anteroposterior, lateral, oblique, and flexion–extension views delineate instability, overall spinal balance and deformity, bony defects, evidence of broken hardware, pseudarthrosis, lysis around implants, and the types of implants that were used. Further characterization of osseous anatomy is best characterized by computed tomography (CT). Magnetic resonance imaging (MRI) with gadolinium contrast can be useful in differentiating scar from other pathologies such as abscess or a recurrent disk. Magnetic resonance imaging can also identify a pseudomeningocele or arachnoiditis; in some cases, a pseudomeningocele can be confused with seroma or infection. Magnetic resonance imaging is limited in cases of excessive postoperative scar and the artifact created by metallic instrumentation. Postmyelography CT scan gives the cleanest image in these cases and is frequently considered the gold standard. Computed tomography allows for the visualization of bony abnormalities and landmarks, the presence of prior laminectomy defects, and the presence of a pars interarticularis defect. In the case of a prior limited decompression, bridging

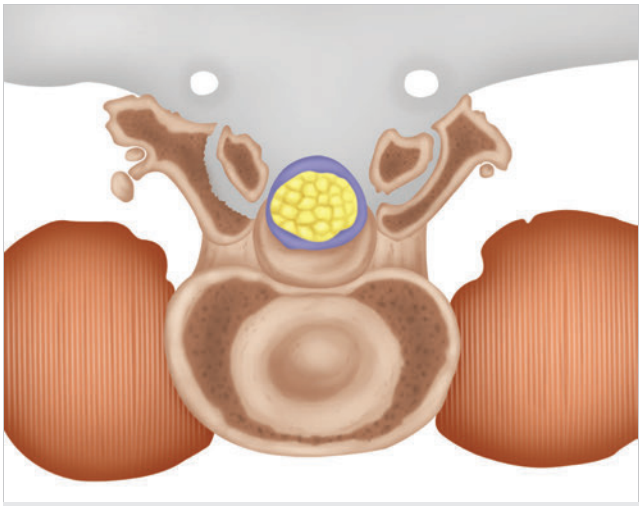

Fig. 107.1 The position of the rods and facets in relation to the dura. These structures may be used as landmarks in estimating the depth of epidural scar resection.

laminar bone can be identified. An important landmark for the safe resection of epidural scar is the midlateral pars and facet joint; this is frequently where the dura is most superficial except at L5–S1 (▶ Fig. 107.1). The dura is frequently superficial to the level of the pars at L5–S1; thus, this landmark is important to guide surgery for scar resection and to avoid an accidental durotomy.

107.6 Special Instructions, Positioning, and Anesthesia

To reduce epidural bleeding a spinal table is used, which minimizes abdominal compression with concomitant increase in intravenous flow to the epidural veins. Attention must be drawn to all external pressure exerted on pressure-sensitive regions during prone positioning, especially pressure over the eyes as well as superficial bony prominences and superficial nerves.

107.7 Difficulties Encountered

One of the most common surgical complications during revision surgery is dural tear with or without persistent cerebrospinal fluid (CSF) leak. Being aware of this potential injury is important as undiscovered dural leaks put the patient at risk for a CSF fistula, pseudomeningocele, and infection. Preoperative CT, myelogram, and MRI will often show evidence of a pseudomeningocele, cysts, or dural outpouching through scar. Durotomy closure can be improved with the use of surgical magnification and monofilament suture. Closure can be augmented with products such as a DuraGen (Integra Life Sciences Corp.) patch or fibrin glue. Even if a durotomy is properly repaired, the patient may have symptoms of postural headache, dizziness, as well as nausea and vomiting. The treatment typically includes bed rest for 48 hours, encouraged fluids, and caffeine.

107.8 Key Procedural Steps

The patient's prior incision is frequently used, although the length may be enlarged to allow for better visualization. In some cases, excision of the prior scar will allow for a better final cosmetic result. Identification of the dura is important as maximal removal of the epidural scar is a goal. Identification of the pars is critical. This can be further elucidated with a CT myelogram. With the exception of L5–S1, where the dura is superficial relative to the pars, it is generally safe to remove scar down to the level of the pars. Meticulous technique is important to avoid an incidental durotomy. A sharp Cobb elevator or curved cervical curette is employed for safe epidural scar removal as it provides tactile feedback when the level of the pars is reached on each side of the canal. Keep the sharp portion of the curette against the bony pars remnant to avoid dural injury. The adjacent lamina above and below the prior laminectomy site should be identified for surgical orientation.

After removing the excessive epidural scar, attention is focused on the decompression itself. It is important to visualize the area of the lateral edge of the spinal canal where the pars and epidural scar adjoin. A sharp cervical curette is useful in removing scare along the bony remnant of the spinal boundaries. In a lumbar revision surgery if a transforaminal lumbar interbody fusion is being performed, a facetectomy can be used to safely define the lateral margins of the dural sac in that region. Bovie cautery must be used with caution to avoid risking thermal injury to the dura. A forward-angle Karlin curette can be useful for further defining the margins of the clearly identified spinal canal. Care needs to be taken in remaining adjacent to the pedicle to avoid injury to the dura and nerve roots as scar is carefully separated from the side wall of the canal. Adherent scar is gently removed above and below the pedicle. This procedure is repeated at the adjacent pedicle if necessary. It is important to identify the nerve root at the level of each pedicle (▶ Fig. 107.2). If a bur is used with care, it may be used to thin the bony remnants of the lateral spinal canal to widen the area of the prior laminotomy. A thin layer of bone may be sculpted at the bone and scar interface and subsequently removed with a forward-angle curette.

107.9 Bailout, Rescue, and Salvage Procedures

Revision decompression surgery is complicated, but can be accomplished by following an organized set of operative guidelines and techniques. Indirect decompression techniques to restore disk height may utilize anterior lumbar interbody fusion, lateral interbody devices, and pedicle screw distraction (unilateral or bilateral). These techniques increase the foraminal area without direct nerve root manipulation. Care should be taken to avoid overdistraction as this may lead to neuropathies from stretch lesions.

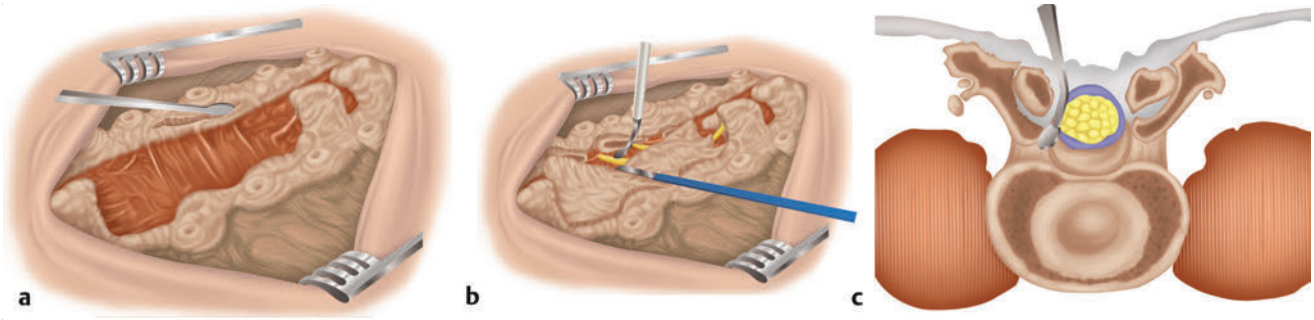

Fig. 107.2 **(a)** There is a lack of definition between the spinal canal and the remaining posterior elements. **(b)** A forward-angle curette may be used to enter the canal at the level of the pedicle. **(c)** A forward-angle curette is used to sweep below and then above the pedicle, gentle removing epidural adhesions.

Pitfalls

- In revision surgery one needs to expect distorted fascial tissue planes.
- In addition, the presence of unappreciated pseudomeningoceles, adhesions, or spinal deformity can create difficulties during surgical exposure.
- Revision procedures often bleed more than primary cases, which contributes to a higher risk of infection. Adequate hemostasis can take longer to achieve and can require more comprehensive techniques including bipolar cautery, thrombin-soaked anticoagulants, Gelfoam (Pfizer Pharmaceuticals), FloSeal (Baxter Healthcare), and tamponade techniques. Bone wax used sparingly can be used to limit bleeding from open cancellous bone, and judicious placement of subfascial drains can limit the accumulation of blood.
- Wounds should be generously irrigated to help lessen the increased risk of infection which accompanies increased intraoperative times. Repeating the use of intravenous prophylactic antibiotics also is appropriate for the longer intraoperative cases.
- Postoperatively patient exams should be frequent and thorough enough to detect hematoma development.
- In the cases that have a cumulative blood loss exceeding one liter, it is appropriate to follow serial complete blood counts, coagulation panels, and electrolytes including calcium.
- Special care and follow-up should be given to patients with medical comorbidities that may require restarting anticoagulants sooner or diabetes, which may mask some of the signs of infection.

108 Effective Use of Intraoperative Hemostatic Agents and Devices to Minimize Intraoperative Blood Loss

Dustin J. Schuett and Nelson S. Saldua

108.1 Description

Intraoperative blood loss in spinal surgery leads to increased transfusion requirements as well as longer hospitalization, and is a primary reason for delaying patient discharge. Surgery to address spinal deformity and revision spinal surgery are associated with substantially greater blood loss than primary and short-segment surgeries. Numerous hemostatic agents and devices have been developed with the goal of minimizing intraoperative blood loss.

108.2 Key Principles

Intraoperative hemostatic agents and devices can be grouped into three categories: systemic, mechanical, and topical hemostatic agents. Systemic hemostatic agents are administered intravenously, typically at the onset or just prior to the onset of the surgical case. Mechanical hemostatic agents are applied directly to the source of bleeding and exert a hemostatic effect by direct pressure. Topical hemostatic agents are applied to and around the source of bleeding and exert a hemostatic effect via a number of chemical and biochemical interactions. Many agents work as a combination of mechanical and topical hemostatic agents (▶ Table 108.1).

108.3 Expectations

The goal of hemostatic agents in spine surgery is to minimize intraoperative blood loss. Surgical blood loss for lumbar fusion surgery averages approximately 800 mL (range 100–3,000 mL) for noninstrumented fusions and over 1,500 mL for instrumented fusions (range 360–7,000 mL). Increased intraoperative blood loss results in increased morbidity and mortality independent of transfusion requirements. Allogenic blood

Table 108.1 Summary of commonly used hemostatic agents

Hemostatic agent	Mechanism of action	Typical use	Contraindications	Adverse events
Tranexamic acid	Inhibition fibrin binding to plasmin	Intravenous infusion; 20 mg/kg loading dose then 10 mg/kg/h	Color vision deficit Active intravascular clotting	Seizures in high dose
Aminocaproic acid	Lysine analogue, inhibition of plasmin	Intravenous infusion, 4–5 g in first hour then 1 g per hour	Active intravascular clotting	Skeletal muscle necrosis
Fibrin sealants	Promotion of fibrin clot formation	Topical application- liquid form	Intravascular application Severe or brisk bleeding	Reduced vascularity to fusion mass Giant cell granulomas
Gelatin sponges	Direct pressure Fibrinogen activation by thrombin	Topical application- pad form	Porcine allergy Intravascular application Autologous blood salvage circuits (Cell-Saver)	Granuloma formation Mechanical compression on cord due to sterile fluid collection
Gelatin matrices	Stimulate intrinsic coagulation cascade Fibrinogen activation by thrombin	Topical application	Porcine hypersensitivity Intravascular application Autologous blood salvage circuits (Cell-Saver)	Granuloma formation Mechanical compression on cord due to sterile fluid collection
Microfibrillar collagen	Activation of intrinsic coagulation cascade and platelets	Topical application- powder form	Bovine hypersensitivity Contaminated wound Implants with methylmethacrylate adhesive	Pain, numbness, paralysis
Oxidized cellulose	Activation of intrinsic coagulation cascade	Topical application- pad and liquid forms	Hypersensitivity to any components Implantation into bone defects	Swelling Giant cell reaction
Thrombin	Converts fibrinogen to fibrin	Topical application- liquid form	Hypersensitivity Intravascular application Severe or brisk bleeding	Viral transmission Elevated INR Prolonged PTT
Synthetic hydrogels	Polymer crosslinking resulting in mechanical adherence	Topical application- liquid form	None known	Localized inflammatory reaction

Abbreviations: INR, international normalized ratio; PTT, prothrombin time.

transfusion carries risk of viral transmission, immunologic reaction, and transfusion-related acute lung injury among other risks. Any intervention that reduces intraoperative blood loss and subsequent need for transfusions would be expected to decrease overall morbidity and mortality.

108.4 Indications

Systemic intraoperative use of hemostatic agents is indicated for use before and during spinal surgery to reduce intraoperative blood loss and subsequent transfusion requirements. Local hemostatic agents are indicated intraoperatively to control bleeding encountered during spinal surgery.

108.5 Contraindications

Contraindications to the use of hemostatic agents are dependent on the individual agent being utilized. Tranexamic acid is contraindicated in patients with active intravascular clotting as well as patients with color vision deficit. Aminocaproic acid is contraindicated in patients with active intravascular clotting. Intravascular application of thrombin and/or fibrin sealants is contraindicated as is its application in the setting of severe bleeding. Gelatin sponges and matrices are contraindicated in patients with a porcine allergy as well as for intravascular application. Additionally, gelatin sponges and matrices cannot be used concurrently with autologous blood salvage circuits (CellSaver) as the gelatin can clog the salvage circuits without specialized filters. Microfibrillar collagen is contraindicated in any contaminated wound, patients with bovine hypersensitivity, and in association with methylmethacrylate adhesive.

108.6 Special Considerations

Tranexamic acid and aminocaproic acid are systemic antifibrinolytics that must be initiated at or just prior to the start of surgery for maximal effect. The efficacy of tranexamic acid has been extensively studied in the total joint arthroplasty literature and early investigations into its use in spine surgery have shown promising results. Tranexamic acid has also been shown to be effective in reducing intraoperative and postoperative blood loss in instrumented spinal fusions. The effectiveness of tranexamic acid is dose dependent with a 20 mg/kg loading dose followed by 10 mg/kg/h infusion resulting in a 50% decrease in transfusion requirements relative to a lower loading and maintenance dose in pediatric scoliosis surgery. Results of aminocaproic acid in spine surgery have been mixed, with some studies demonstrating decreased blood loss and transfusion requirements in patients undergoing surgery for idiopathic scoliosis and neuromuscular scoliosis, whereas other studies found no benefit in major orthopaedic surgeries.

Fibrin sealants assist in hemostasis via promoting formation of a stable fibrin clot. The majority of commercially available fibrin sealants contain fibrinogen, Factor XIII, thrombin, and antifibrinolytics (typically tranexamic acid and aprotinin). Fibrin sealants typically have fibrinogen and thrombin in separate syringes, this allows simultaneous delivery of the compounds into the wound with the combination of the components in the presence of calcium resulting in their activation. Proteins and stabilizing agents contained in the compounds determine the time to fibrin clot formation. There are several types of fibrin sealants commercially available including EVICEL (Johnson & Johnson), Quixil (Omrix Biopharmaceuticals), TISSEEL (Baxter Healthcare), and Vitagel (Orthovita). All of these except Vitagel contain human thrombin and fibrinogen; Vitagel contains bovine thrombin and collagen. Bovine thrombin has been associated with the development of antithrombin and antifactor V antibodies and presents the risk of transmission of zoonotic disease, specifically bovine spongiform encephalopathy. All human and bovine plasma components undergo extensive viral inactivation precautions. The application of topical fibrin sealants in adults undergoing elective orthopaedic surgeries has been shown in a large meta-analysis to decrease blood loss by a mean of 223 mL per patient and resulted in a 32% reduction in allogenic blood transfusion. In spine surgery specifically, fibrin sealants have also been shown to be effective in sealing dural tears. Fibrin sealants have been shown to decrease drain output and length of hospital stay in patients undergoing multilevel anterior cervical fusions, resulting in an average cost savings from shorter hospitalizations of $133 per patient.

Gelatin sponges were first described for use as hemostatic agents nearly 70 years ago. Gelatin sponges are approved by the Food and Drug Administration for use in surgical procedures as a hemostatic agent when control of bleeding by pressure, ligature, and other conventional procedures is either ineffective or impractical. Commercially available examples of Gelatin sponges include Gelfoam (Pfizer Pharmaceuticals) and SURGIFOAM (Johnson & Johnson). The sponges are applied directly to the site of bleeding and may be used with or without thrombin to augment the hemostatic effect. The modern gelatin sponges are composed of porcine gelatin and function via stimulation of the intrinsic coagulation pathway from direct collagen exposure. Additionally, gelatin sponges can absorb over 40 times their weight in blood. In vivo, gelatin sponges are absorbed by the body within 4 to 6 weeks. Their use and application is fairly straightforward and at a relatively low cost. There are numerous gelatin matrices commercially available in the United States including SURGIFLO (Ethicon) and FloSeal (Baxter Healthcare). The active components of gelatin matrices are gelatin microgranules with thrombin (FloSeal) or without thrombin (SURGIFLO). These microgranules stimulate the intrinsic coagulation pathway, and thrombin activates fibrinogen. Their primary advantage is improved hemostasis and decreased local swelling over gelatin sponge alone. In a head-to-head comparison in patients undergoing spinal and orthopaedic surgery, gelatin matrices resulted in hemostasis in 98% of patients compared to 90% of patients for gelatin sponges alone within 10 minutes of application.

Microfibrillar collagen (Avitene Flour by Davol and Instat MCH by Ethicon360) is bovine collagen in a web or powder form that acts via activation of the intrinsic pathway and platelets resulting in hemostasis at the risk of severe granulation. Microfibrillar collagen has been demonstrated to be superior to oxidized cellulose; however, it has not been widely compared to more commonly used hemostatics including gelatin foams and matrices.

SURGICEL (Johnson & Johnson) and Oxycel (Becton) are examples of plant-based oxidized cellulose topical hemostatic

agents that activate the intrinsic pathway and may potentially have bacteriostatic effects due to their acidity. Like all collagen-based topical hemostatics, oxidized cellulose requires normal coagulation cascade function.

108.7 Special Instructions, Positioning, and Anesthesia

Combinations of multiple hemostatic agents specifically thrombin and absorbable gelatin compressed sponges have proven effective in decreasing postoperative drain output and hospital stay following cervical spinal surgery. The data for other combinations of hemostatic agents in spinal surgery are sparse and inconclusive in regards to efficacy as well as safety; however, the use of combinations is prevalent.

Operative positioning may play a role in intraoperative blood loss. A wider support pad width while using the Wilson frame decreases both intra-abdominal pressure as well as blood loss.

The use of controlled hypotension has long been used to reduce intraoperative bleeding in spinal surgery; however, ischemia in end organs, most commonly in the eyes, has been reported. Current recommendations are to maintain systolic blood pressure 20 to 30% below the patient's preoperative baseline with close cardiac, neurophysiological, and intravascular monitoring.

108.8 Tips, Pearls, and Lessons Learned

The incidence of vertebral artery injury in anterior cervical spinal injury is reported to be 0.3%. In the event of inadvertent vertebral artery injury, tamponade via direct pressure is the initial step. Ligation distally and proximally is considered an undesirable option resulting in possible brainstem infarction in up to 4% of cases. When possible, direct repair is preferred and most readily performed at the level of the transverse process directly over the transverse foramen. The longus coli muscle is elevated and the undersurface of the costal process is freed of overlying soft tissues. Proximal and distal control of the artery is obtained using right angles and vessel loops, and a direct repair is performed. Vascular surgery consultation may be required. Irreparable injuries may be treated with an endovascular stent. Intraoperative angiography may help determine the adequacy of collateral circulation in the event that ligation is to be performed.

108.9 Difficulties Encountered

Intraoperative hypotension has long been known to have the potential to cause ischemic optic neuropathy. Seizures have been observed in patients receiving high-dose tranexamic acid. Aminocaproic acid has been associated with skeletal muscle necrosis. Granuloma formation and spinal cord compression from sterile fluid collection has been reported with gelatin sponges and matrices as well as fibrin sealants and oxidized cellulose. Use of any products with porcine or bovine components presents the risk of a hypersensitivity reaction. Use of human-derived components carries the risk of disease transmission.

108.10 Key Procedural Steps

Tranexamic acid is typically administered intravenously in a 20 mg/kg loading dose followed by 10 mg/kg/h infusion for the duration of the case. Aminocaproic acid is given with a 4- to 5-g loading dose in the first hour then 1 gram per hour. Fibrin sealants, gelatin sponges, gelatin matrices, microfibrillar collagen, oxidized cellulose, thrombin, and synthetic hydrogels are all applied topically.

108.11 Bailout, Rescue, and Salvage Procedures

A large systematic review found little support for routine use of Cell-Saver during elective spinal surgery. Intraoperative use of topical hemostatic agents allows rapid control of intraoperative bleeding; most result in hemostasis within 10 minutes.

Pitfalls

- Anaphylaxis and cauda equine syndrome has been reported secondary to sterile fluid collections resulting from the use of collagen-based hemostatics.
- Decreased vascularity to the fusion mass in spinal fusion procedures has been seen in canine and feline models with use of fibrin sealants; however, there has been no causal relationship proven between fibrin sealant use and pseudarthrosis in humans.

109 Managing Catastrophic Great Vessel Injury in Surgery on the Thoracolumbar Spine

Cristian Gragnaniello, David Robinson, Remi Nader, Kevin Seex, and Alexander R. Vaccaro

109.1 Description

Vascular complications in thoracolumbar spine surgery are either a result of direct physical injury to the arterial and venous system or due to indirect injuries due to hypotension that may result in ischemia to the neural elements. Direct injuries can be immediate or delayed. Immediate injuries include physical laceration of a vessel or traction injuries that may result in vessel injury and subsequent hemorrhage. Delayed causes include compression and subsequent clotting or erosion injuries due to pressure from contiguous instrumentation.

Possible consequences of injuries to the vasculature other than hemorrhage include formation of aneurysms and arteriovenous fistulas.

109.2 Key Principles

Although most direct injuries to large vessels can be successfully managed intraoperatively or with emergent endovascular intervention, it is more important for surgeons to know how to avoid such injuries. If such an injury occurs, early recognition allows for greater time to prepare equipment and personnel.

In the last two decades, with the development and refinement of anterior surgical approaches to the spine, there has been an increase in reported vascular complications. Preoperative timeout should include the presence of available blood products and the necessary staff available if a vessel injury does occur, including an access or, vascular surgeon, or surgeon experienced in vascular repair if the initial approach is being performed by an orthopaedic or neurosurgeon. The anticipated amount of blood loss should be discussed with the surgical team including the anesthesiologist as well as preferred hemodynamic parameters.

109.2.1 Incidence

In anterior thoracic spine surgery the reported rate of paraplegia due to indirect (stretched induced ischemia) vascular injury had been reported to be as low as 1% in a large series of thoracic deformity-correction surgeries. The reported vascular complication rate in lumbar anterior lumbar interbody fusion (ALIF) or total disk replacement procedures (TDR) is reported to be between 1.3 to 15.6%. The incidence of vascular injury via a posterior lumbar surgery is around 0.05%.

109.3 Expectations

Following physical injury to a vessel, there should be vascular control and repair of the injured vessel(s) with avoidance or limitation of adverse sequelae to other organs and systems.

109.4 Indications

Recognized catastrophic vascular injury after an anterior or posterior thoracolumbar approach to the spine

109.5 Contraindications

Avoid situations if possible where an anterior exposure may be at risk for a direct vessel injury such as in a radiated surgical field or at the site of previous anterior surgery.

109.6 Special Considerations

Vascular injuries related to spinal procedures have been classified mostly with regard to the anatomical location of the vessel injured and according to the type of surgical approach.

Following an anterior lumbar retroperitoneal approach, the most common vessel injured is the left common iliac artery. Significant complications may include ischemia, infarction, and loss of limb or life. Injury to the left common iliac vein can be difficult to repair and may result in vessel thrombosis, especially if suture repair is required, as a result of vessel diameter narrowing and altered blood flow.

109.7 Special Instructions, Positioning, and Anesthesia

- When operating anteriorly in the thoracic and thoracolumbar spine, especially in revision cases where the blood supply to one side of the spinal cord may be impaired or in complex deformity cases, there is a potential risk of ischemia due to segmental vessel disruption.
- In revision scoliosis surgery, if possible, one should consider approaching the spine through the already dissected side to minimize risk of spinal cord ischemia by disrupting blood supply to the contralateral intact side.
- Bilateral first toe pulse oximetry is used for early detection of arterial vessel occlusion in anterior lumbar procedures.
- Cell-Saver is a valuable adjunct in case of expected significant blood loss.
- Available instruments should include right-angle hemostats, vascular clips, ligature and Ligaclips, and appropriate sutures.

109.8 Tips, Pearls, and Lessons Learned

- Prior to ligation of anterior segmental arteries, especially if sizeable, a temporary clip should be placed followed by neurophysiologic monitoring for up to 5 minutes as a change in potentials may indicate the danger involved with vessel sacrifice.

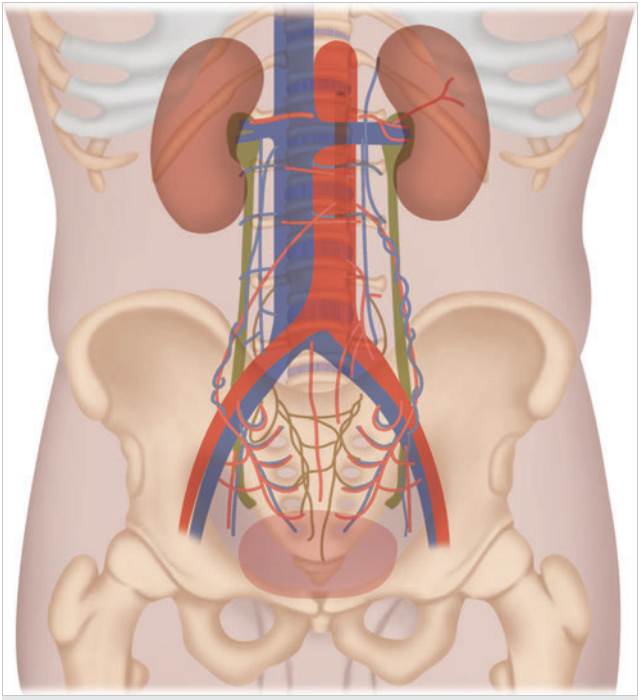

Fig. 109.1 Vascular anatomy relevant to the anterior lumbar spine.

- To avoid ligature or clip dislodgement one should double ligate, ligate and clip, or double clip each side of the vessel where ligation is anticipated.
- Exposure of the disk space at L4/5 and above requires mobilization and ligation of segmental vessels. It is far easier to mobilize the aorta, left common iliac, and left common iliac vein from the left to the right than it is the potentially friable and less forgiving vena cava on the right (▶ Fig. 109.1).
- Patient positioning is important in potentially avoiding vascular complications. For example, in the posterior approach to the lumbar spine in an obese patient, the abdominal pannus should be protected and in a gravity-dependent position (i.e., open Jackson table) to avoid pressure to intra-abdominal contents that may potentially push the great vessels in close proximity to the anterior anulus. One can measure the depth of the disk space on the transaxial imaging studies to know the safe depth of placement of surgical instruments.

109.9 Difficulties Encountered

- During surgical dissection around major vascular structures in the setting of an inflammatory or infective process, possible involvement and weakening of the vessel walls may increase the potential of vascular injury. Direct suture repair is more difficult in these cases.

109.9.1 Anterior Thoracic Spine

- Transthoracic approaches may require mobilization of segmental arteries over several levels. On the left side, the heart and potential injury to the vessel of Adamkiewicz may complicate this exposure.
- Anterior instrumentation for thoracic scoliosis puts at risk the great vessels because of the proximity of these vessels to the screws/rods or protruding screw tips on the other side of the spine.

109.9.2 Posterior Thoracic Spine

- The most common vascular complication following a posterior approach is direct injury to an intercostal artery, especially if rib resection is necessary. If the injury is not recognized it has the potential to result in a significant delayed hemothorax.

109.9.3 Lumbar Spine

- When exposing the L4/5 disk anteriorly it is often necessary to sacrifice the iliolumbar vein. Traction on this vessel may result in rupture and significant blood loss.

109.10 Key Procedural Steps

The first response to abrupt hemorrhage is local control with pressure, and concurrent team communication about the event and immediate need requirements (i.e., second suction, blood pressure, and volume control). Control can simply be via local pressure with a peanut or swab on a stick.

109.10.1 Visualization

Visualization of the direct vascular injury is the next step in achieving effective vascular control. A combination of two large bore suckers is required: one to find the source of blood and the other to clear the operative field of blood already present.

109.10.2 Avulsion of Segmental Vessel

A large volume of blood can be lost over a short period following a segmental vessel traction avulsion: bleeding needs to be controlled immediately by direct pressure.

109.10.3 Anterior Lumbar Spine

Control and repair of a direct vascular injury varies according to the stage of the surgery during which it occurs and also, naturally, the nature of the injury and the type of vessel affected.

The majority of vascular injuries are relatively straightforward to repair with direct suture; however, in more difficult situations, options of graft repair or other more complex techniques require a vascular surgeon's expertise.

The defect in the vessel wall will depend on the mechanism of injury. The most common mechanism relates to avulsion of a segmental vessel during mobilization, leading to a focal defect. Control of bleeding with well-directed pressure will allow primary repair by monofilament, nonabsorbable suture.

A bur injury to a vessel will lead to a more extensive defect that is less likely to be amenable to primary repair. In the uncommon situation that a surgical instrument penetrates a vessel and is recognized prior to its removal and hemostasis is adequate, it may be better to leave the instrument in place

while exposure is improved to allow optimal vascular control. It is imperative that an adequate exposure is provided before definitive vessel repair is attempted. During this time hemorrhage is controlled with focal pressure or packing. Further access can be provided by converting a retroperitoneal approach into a transperitoneal approach. Repair of the vessel may be via a direct repair, an interpositional graft or patching, or endovascular repair with stent-grafting.

Autologous grafts that are readily available include the great saphenous vein (better suited for patching due to small size) and the femoral vein.

A laceration to the left common iliac vein is difficult to repair due to its position deep to the artery. In some cases with an extensive or complicated venous defect it may be easier to divide the artery to gain access to the vein for control and repair of the hemorrhage, followed by an end-to-end repair of the artery once the vein is successfully repaired or ligated.

In some, ligation of the common iliac vein is necessary. Ligation of the vein is generally well tolerated.

Arterial thrombosis is uncommon, and is most likely related to a flow-limiting dissection of the vessel intimal wall due to vessel retraction or mobilization, particularly in the setting of a diseased arterial tree. The disease state of the vessel may be recognized preoperatively on spinal imaging or from a history of peripheral vascular disease. When an arterial thrombosis is recognized intraoperatively, either from the absence of pulsation in the affected segment or due to dampening of pulse oximetry tracing in the foot, immediate exploration and repair is the best option for minimizing ischemic time. This may be done via an open arteriotomy, repair of the dissection and patch angioplasty closure, or a thrombectomy with a Fogarty catheter. Alternatively, endovascular access may be obtained from the ipsilateral groin with subsequent placement of a stent to reestablish blood flow.

At L5–S1 the left common iliac vein is primarily at risk, and at L4-L5 and L3-L4 the vena cava and aorta along with branches of the common iliac artery and vein are at risk. The recurrent or ascending iliolumbar vein is a significant source of hemorrhage when exposing the L4-L5 disk space as it arises from the common iliac vein posterior or posterolaterally and can easily be avulsed if not divided prior to mobilization of the left common iliac vein.

Injury to the inferior vena cava (IVC) may require tying off the IVC as the best course of action, especially in a patient receiving a massive transfusion, and in whom a delayed leak from an anastomosis would be life threatening. Complete occlusion of IVC is likely to be survivable albeit with consequences of lower limb edema and potential varicose ulcerations.

109.10.4 Lateral Approach to the Lumbar Spine

Vessel injury is a potential with the lateral anterior approach to the lumbar spine. It is more common at the L4/5 level due to the close proximity of the iliolumbar vein and a tendency for a more anterior approach to the disk space to avoid injury to the lumbar plexus lying within psoas.

The presence of scoliosis may rotate the vessels into the path of surgical instruments on both the ipsilateral and contralateral side of the spine. A slightly oblique approach to the spine anterior to the psoas also brings the surgical dissection in close proximity to the great vessels. Vascular anatomy should be reviewed preoperatively on the lumbar advanced imaging studies to be prepared for any unusual vascular variants.

109.10.5 Posterior Lumbar Spine

The most common mechanism of vascular injury through a posterior lumbar approach is placing an instrument such as a curette or a pituitary rongeur through the anterior disk space causing a pinching or tearing injury to the vessels anterior to the disk space. Interestingly, the rate of reported injuries does not seem to be different in complete diskectomies for a fusion or a microdiskectomy. Injuries described have included laceration of the IVC, aorta, iliac vessels, pseudoaneurysm, and arteriovenous fistula. In injuries to the iliac vessels, hypotension may be delayed and should raise suspicion for a vascular injury if this occurs. Further injury to a diseased vessel is possible with rupture of an aortic aneurysm or injury to a calcified artery. Risk factors include previous anterior abdominal surgery and retroperitoneal inflammation, which contribute to adhesions of the vessels to the spine. Anular tears in the anterior part of the disk in the setting of increased abdominal pressure may increase the risk for vessel injury. Brisk bleeding or blood rapidly pooling in the operative field only occurs in half the cases, as the bleeding may primarily occur in the retroperitoneum. If brisk bleeding occurs, the wound should be packed and volume expanders started while preparing the patient for the supine position and an anticipated laparotomy.

If hypotension occurs without an evident source of vascular injury, one may fill the wound with saline to see if it rapidly escapes into the retroperitoneum confirming the presence of an anterior anular tear (Shevlin's test).

109.11 Bailout, Rescue, and Salvage Procedures

- In cases of direct injury to major vessels during a minimally invasive anterior thoracic procedure, an immediate conversion to open thoracotomy is necessary along with the needed assistance of a trained vascular surgeon.
- Direct vascular injuries during posterior thoracic and lumbar approaches require immediate wound packing followed by placing the patient in the supine (lumbar) or lateral (thoracic) position in anticipation of an emergent anterior exposure.
- A problematic vascular injury is one that occurs in the early portion of the exposure when there is minimal vascular exposure. In this case, apply pressure, inform the team of the event, and enlist additional assistance. Attempting a direct repair without adequate exposure is unwise.
- When approaching the spine anteriorly in a revision case, it may be wise to prep the groin for placement of a catheter balloon to arrest bleeding if necessary.

Pitfalls

- Revision anterior lumbar surgery should be avoided if possible because of the high incidence of vascular injury (up to 50%) in approaching previously operated levels.
- Ligation of segmentals is safer at the level of the thoracic aorta when done at about 1 cm from the parent vessel to avoid creating a hole on the side of the artery. Vessels ligated closer to the parent vessels have been noted to develop better delayed collateralization than those ligated further from the parent vessel.
- Performing an anterior approach to the L5/S1 disk in the elderly can be technically difficult as 20% of patients have a bifurcation at or below the level of the disk space, thus requiring mobilization of the left common iliac vein and artery, which can be hazardous if the vessels are calcified (see ▶ Fig. 109.2).
- Potentially fatal complications of vascular repair include reperfusion syndrome and multiple organ dysfunction. Early recognition of large vessel occlusion is as important as prompt repair of an acute injury.
- Having to reoperate through an anterior approach in someone in whom no antiadhesive barrier has been placed around the vessels may increase the risk of vessel injury. If the vessels are scarred to the anterior surface of the spine, one should use sharp dissection to elevate the vessels and avoid any traction to the vessels as this may result in rupture.
- For a revision anterior reoperation at L5/S1, consider approaching the spine from the contralateral side to the first approach, as the retroperitoneal plane will not be disturbed and may enable more effective retraction while approaching the anterior disk.

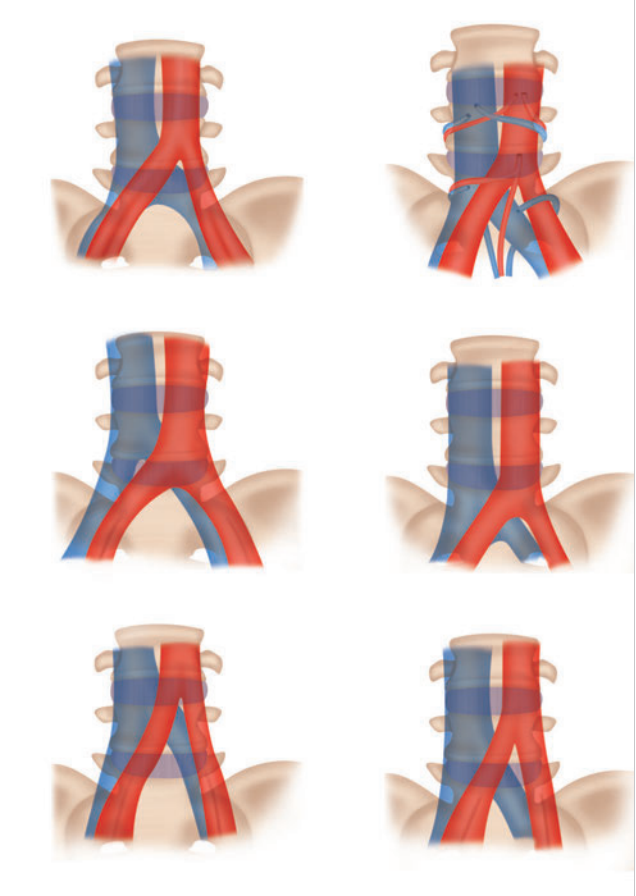

Fig. 109.2 Possible variation of the bifurcation of the iliac vessels at the level of the L5/S1 disk space.

110 Dural Repair and Patch Techniques: Anterior and Posterior

Gregory Gebauer

110.1 Description

Dural tears are frequently encountered during routine spine surgery. These can occur incidentally during routine decompression surgery or can be anticipated preoperatively depending on the pathology, such as ossification of the posterior longitudinal ligament, a traumatic burst fracture, lamina fracture, or intradural lesion. Multiple repair techniques are available, including primary suture closure, dural grafting, and various glues. In some patients, a period of bed rest flat (for lumbar tears) or maintenance of an elevated head position (cervical tears) may be appropriate. Symptoms of cerebrospinal fluid (CSF) leakage from a dural tear include postural headaches, nausea, and dizziness.

110.2 Key Principles

Identification and treatment of dural tears at the time of index surgery is essential and provides the best opportunity for successful treatment and minimizes the risk of complications. Delayed or missed dural tears should likewise be treated promptly. When possible, primary closure of the defect should be performed.

110.3 Expectations

Incidental dural tears can occur even in the most experienced hands. The incidence during primary lumbar decompression ranges from 3 to 7% and increases to 8 to 16% in revision cases. The incidence is lower in cervical surgery, but has been reported in 1% of anterior cervical decompression cases. When effectively treated, incidental durotomies have not been shown to alter long-term clinical results. Risk factors for dural tears include ligament ossification, advanced age, revision surgery, the presence of a synovial cyst, and surgeon experience.

110.4 Indications

Any dural tears encountered during surgery should be addressed at that time. Injury to the dura with an intact arachnoid membrane (dural bleb) should also be treated to prevent later CSF leakage. For patients with missed or delayed dural tears who have symptoms of CSF leakage, a trial of nonoperative care including bed rest can be considered prior to surgical exploration and dural repair.

110.5 Contraindications

With few exceptions, all dural tears noted intraoperatively should be repaired. For patients with missed or delayed CSF leaks who have not responded to a trial of bed rest, surgical repair should be considered.

110.6 Special Considerations

Preoperative planning is essential. The surgeon should be familiar with the instruments, suture materials, grafts, and adjuncts available in the case of an incidental durotomy. In cases where there is a high likelihood of a dural tear, such as ossification of the posterior longitudinal ligament, the surgeon should have a plan for handling the dural tear prior to the surgery. In all cases, the risk of a dural tear should be discussed with the patient as part of the informed consent process.

110.7 Special Instructions, Positioning, and Anesthesia

Once a dural tear is identified, positioning the patient in a Trendelenburg position may help decrease some of the fluid leakage. This position should be reversed when testing the adequacy of the repair. In addition, an anesthesiologist can perform a Valsalva maneuver to determine if there is any residual fluid leakage after repair is complete to help identify any small or pin-hole size tears that might otherwise go missed.

110.8 Tips, Pearls, and Lessons Learned

Adequate visualization is essential. A microscope or surgical loops should be used. The surgeon should plan ahead and have available the necessary instruments, sutures, patches, and glues needed for dural repair. Specialized surgical instruments include microscissors, microneedle holders (such as Castroviejo's), knot pushers, and knot-tying forceps. 5–0 or 6–0 Nurolon, Gore-Tex, or Prolene sutures should be available. There are many grafts available including synthetic collagen matrix grafts, allografts (such as fascia lata graft) and xenografts (such as bovine pericardium). Autograft fascia lata can be used, but this requires a separate incision and unless a dural tear is anticipated, it is not usually included in the surgical field. Fibrin glues are also available. The surgeon should be familiar with the properties of the specific fibrin glue to be used as some are hydrophilic and can expand once placed in the body. Rare cases of cauda equina syndrome and nerve compression have been reported.

The presence of a dural tear with exposure of the central neural elements places the patient at risk for meningitis. Appropriate antibiotic coverage, such as the use of ceftriaxone, should be considered. Postoperatively the patient should be examined for nuchal rigidity, photophobia, and headaches.

For patients who present with symptoms of a missed or delayed dural tear, magnetic resonance imaging (MRI), computed tomography (CT) myelogram, or radionuclide cisternography can help to identify the leak. Fluid from the wound can also be aspirated and sent for beta-2 transferrin, the presence of which confirms the fluid is CSF.

110.9 Difficulties Encountered

Nerve rootlets can often extrude through lumbar dural tears. These should be handled with great care. Cottonoids and small-diameter Frazer-tip suction should be used to prevent them from being caught in the suction. Gentle manipulation should be used to return the rootlets into the thecal sac. It may be necessary to enlarge the dural defect to allow for easier return of the rootlets. Once the rootlets are back in the thecal sac, the dura should be gently lifted with blunt forceps while passing a suture to avoid entrapping the rootlets. Occasionally, the passing of the needle through the dura may also create small areas of leakage. The repair can be augmented with an onlay graft or fibrin glue.

Large defects may not be amendable to primary repair. Primary repair should not be performed if it places the dura under tension or could constrict the nerves. These defects may require the use of a dural patch (described in more detail below). Tears encountered during anterior surgery or those that occur on the ventral thecal sac during posterior surgery may be especially hard to repair given the limited exposure and access to these areas; they may be best treated with patching techniques.

110.10 Key Procedural Steps

Once a tear is noted, a cottonoid should be placed to help stem the flow of CSF. Further decompression should then be performed until the defect can be fully visualized and there is adequate space for the passage of instrumentation. Hemostasis should be achieved to help with visualization. The size and the shape of the dural tear will dictate the treatment strategy (▶ Fig. 110.1).

For lumbar tears, cottonoids and Frazer-tip suction should be used to avoid inadvertently suctioning any nerve rootlets. If any rootlets have extruded through the defect, these should be gently maneuvered back into place with the use of a nerve hook. When possible, primary repair using either a 5–0 or 6–0 Gore-Tex, Prolene, or Nurolon should then be perfomed. The dura should be gently lifted either with forceps, a nerve hook, or with stay sutures placed on the edges of the tear to elevate the dura away from the underlying nerve rootlets (▶ Fig. 110.2). Castroviejo or Ryder needle drivers may help with passing the suture. Interrupted or running locking sutures can used. Once suturing is complete, a Valsalva maneuver should be performed to ensure that there is no residual leakage. If necessary, the repair can be reinforced with an onlay graft and/or fibrin glue.

Injury only to the dura and not to the arachnoid layer without leakage of CSF (dural bleb) should be repaired. Smaller defects may be treated with just an onlay graft or fibrin glue. Larger defects may still require sutured closure.

For larger lumbar tears that are not amenable to suture repair, a graft can be used. Lumbar or thoracodorsal fascia, fat, and muscle are often available through the same incision. Fascia lata is an excellent graft option, but requires a separate incision and separate surgical prep. Allografts, xenografts, and collagen matrix grafts are also options. These should be sutured to the dura at the edges of the defect (▶ Fig. 110.3). If possible it may be advantageous to place the graft below the edge of the dura so that pressure from the CSF will press the graft into the dura. These grafts can likewise be reinforced with fibrin glues.

Fig. 110.1 Examples of the different types and locations of dural tears. Type A tears can be repaired primarily, whereas type B opening requires patch technique. Types C and D tears should be considered for fat, fibrin glue, or collagen matrix onlay bailout.

A watertight layered closure should then be performed. Absorbable suture such as Vicryl may degrade in the presence of CSF and consideration should be given to oversewing the fascia with a nonabsorbable suture such as Nurolon, Maxon, or

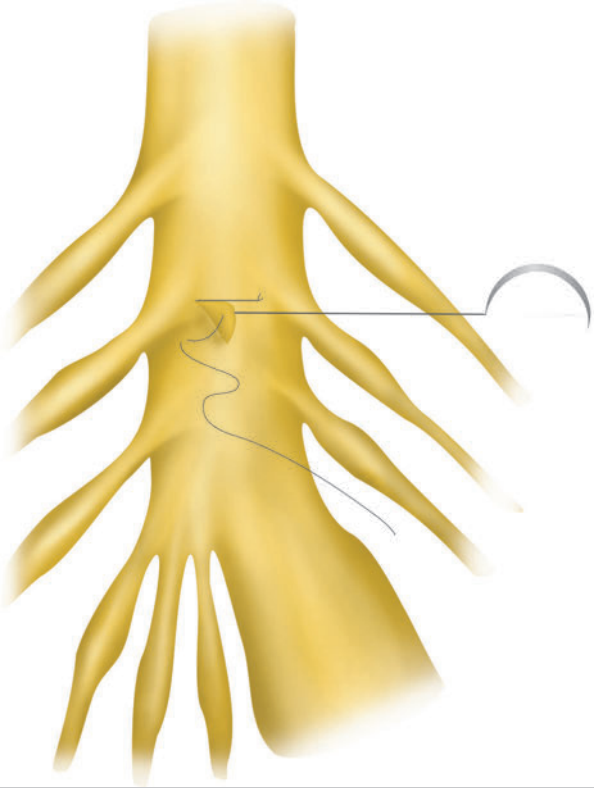

Fig. 110.2 The graft is tacked into place with stay sutures in all corners.

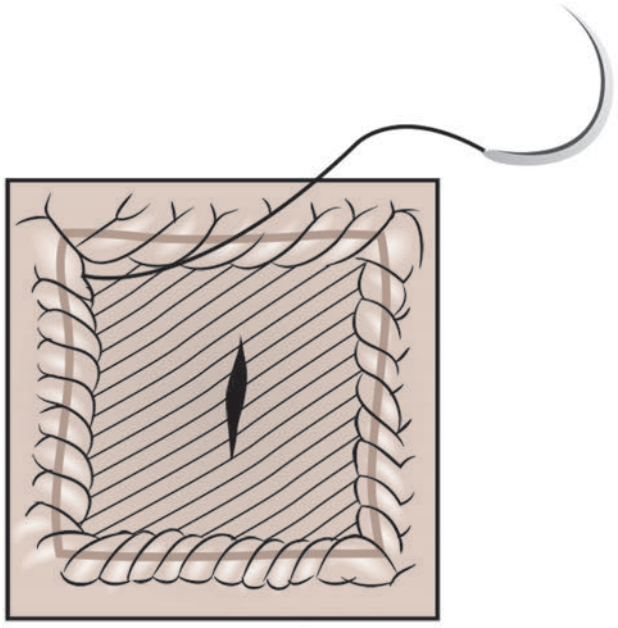

Fig. 110.3 The repair is completed with interrupted or running sutures.

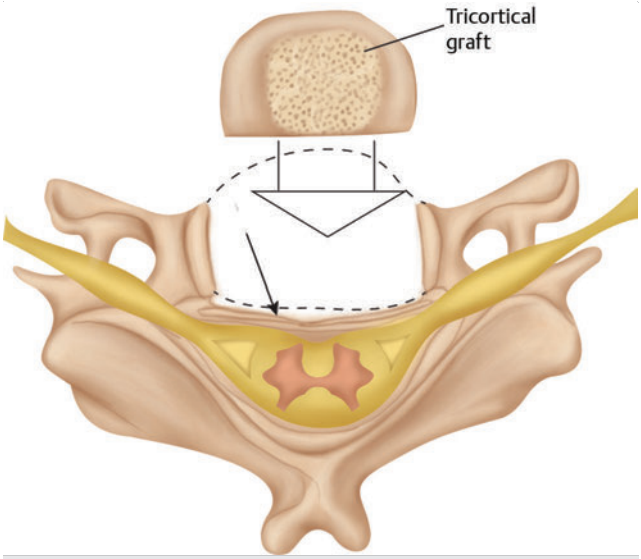

Fig. 110.4 A small dural defect (black arrow) during an anterior cervical diskectomy or corpectomy may be difficult to widely expose for repair. The large arrow shows the tricortical graft placement.

Prolene. The use of drains below the fascia is controversial, but if they are used they should be placed to gravity and not to suction.

Postoperatively, the patient should be kept on bedrest with the head of the bed flat. There is no clear recommendation for the length of time a patient should be kept on bedrest; in general, patients with larger defects or poorer quality repair may require longer periods of recumbency. Once the surgeon decides that it is alright to begin mobilizing the patient, the head of the bed can be slowing elevated, generally starting at 30 degrees and increasing by 10 degrees every hour or 2 hours. If headaches develop, the patient should be returned to flat bedrest. The patients should be kept on intravenous fluids to ensure adequate hydration. Caffeine may help to treat some of the headache symptoms.

Anterior tears, either encountered during an anterior procedure or while accessing the disk space during posterior procedures, are challenging as primary repair is not possible due to difficulties passing instruments at the site of the repair. Onlay grafts with fat, muscle, or collagen sponges with or without fibrin glue can be used (▶ Fig. 110.4, ▶ Fig. 110.5). During anterior procedures, these should be placed into the disk space prior to placement of the bone graft or cage. For posterior procedures, such as a transforaminal interbody fusion, these grafts can be placed into the disk space following placement of the bone graft or cage.

Cervical tears are less common than lumbar tears, but can still occur. Similar repair techniques, including primary sutured repair when possible, should still be performed. Postoperatively, patients should be positioned with the head of the bed elevated (as opposed to lumbar tears where the patient is kept flat) as this decreases the CSF pressure at the site of the injury.

110.11 Bailout, Rescue, and Salvage Procedures

Subarachnoid drains can be used for patients with inadequate repairs or who are unable to undergo surgical repair. These drains are placed using a technique similar to the administration of spinal anesthesia, with a catheter inserted over a needle.

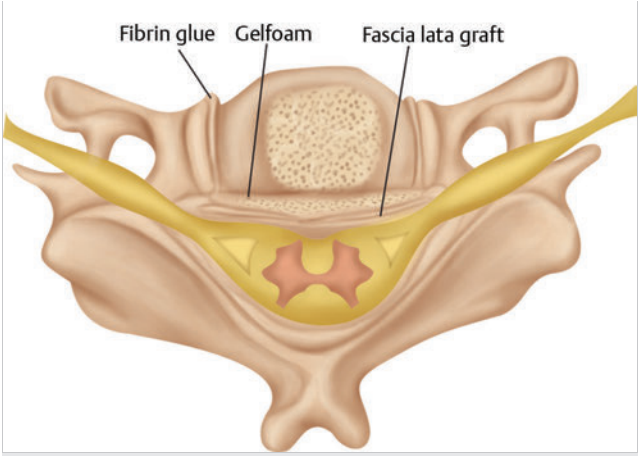

Fig. 110.5 Autologous fascia or fat or collagen matrix is laid gently over the defect and held in place with a piece of Gelfoam (Pfizer Pharmaceuticals). Fibrin glue is added to secure the fascial graft, and a tricortical bone graft is placed in the usual fashion. It is important to measure the depth of the corpectomy defect to avoid iatrogenic spinal cord compression. Once the graft is in place, more fibrin glue can be added in the lateral gutters.

Protocols vary, but in general between 120 and 360 mL are drawn off every day for between 4 and 10 days. Patients should be placed on prophylactic antibiotics and monitored for potential overdrainage of fluid, which may lead to potential neurologic decline.

Pitfalls

- The dura, especially in older patients, can be extremely friable and care should be taken during its handling and suture to prevent worsening of the tear. Nerve rootlets may often extrude through the dural tear; extreme care should be taken to avoid entrapping these rootlets in the suture repair.
- For anterior thoracic dural tears, care should be taken to isolate the tear from the pulmonary compartment as the negative pressure associated with respiration can worsen the dural injury and even suck CSF from the wound. Any chest tubes should be monitored to see if there is CSF within the drainage. The patient's neurologic status should be closely monitored for any signs of decline that could suggest an uncal herniation.
- Despite the literature showing no adverse effects on long-term results, dural tears can lead to potential litigation against the surgeon. The risk of these tears occurring should be discussed in detail with the patient as part of the informed consent process.

111 The Surgical Management of Junctional Breakdown above a Spinal Fusion in the Thoracic and Lumbar Spine

Timothy Tan, Paul W. Millhouse, and Stewart Kerr

111.1 Description

Junctional breakdown above prior instrumentation is a common complication of long spinal fusions and poses a unique challenge to the deformity correction surgeon. Although the etiology of junctional breakdown is not completely understood, it is believed to result from physiological responses to biomechanical stresses resulting from loss of motion at the adjacent fusion site and changes in sagittal balance. Breakdown can present as worsening spinal pain or return of spinal pain with symptoms of neurologic compromise such as neurogenic claudication (leg weakness, radiating leg pain, and lower extremity sensory deficit) or myelopathy.

111.2 Key Principles

Identification of the etiology of junctional breakdown is imperative if possible. This requires an understanding of the desired or required sagittal alignment, the patient's bone mineral density, and other comorbid conditions.

111.3 Expectations

Adjacent segment junctional breakdown has been noted to occur in 55 to 72% of patients 10 years following a spinal fusion and is correlated with statistically significant differences in Oswestry Disability Index (ODI) and patient pain scores. When effectively managed, this condition does respond well to surgical treatment.

111.4 Indications

Indications for surgical intervention related to junctional breakdown above a fusion site include radiographic deformity, medically refractory pain, ambulatory dysfunction, poor maintenance of chin-brow-to-vertical angle (CBVA), spinal cord dysfunction (myelopathy), medical or psychological conditions resulting from abnormal posture, and neurogenic claudication refractory to nonoperative care (i.e., patient-accepted activity modification, oral analgesics / nonsteroidal anti-inflammatory drugs, epidural steroid injections).

111.5 Contraindications

Surgical management should be considered if the above indications are present and if the patient is able to tolerate the surgical stress of correcting the junctional breakdown. For patients who are too ill for operative treatment, continued conservative care is advised. Potential contraindications to surgery include significant medical comorbidities, multilevel neoplastic disease, and possibly severe osteoporosis. Relative contraindications include systemic issues such as malnutrition or anemia, respiratory compromise, severe depression, psychosocial problems, and secondary gain issues.

111.6 Special Considerations

Careful analysis of the patient's bone quality / density and comorbidities is essential. For example, surgical correction of a single level adjacent to previous instrumentation in an otherwise healthy middle-aged adult is typically very simple with expected excellent patient satisfaction outcomes. This is radically different from the surgical morbidity associated with correcting an elderly, frail osteoporotic patient with proximal upper thoracic kyphosis above a long instrumented scoliosis fusion (▶ Fig. 111.1). All relevant patient factors should be discovered, scrutinized, and appropriately examined. Careful presurgical planning is paramount and must consider any special surgical equipment or instrumentation. Proper surgical team coordination, especially with regard to specific anesthesia considerations, is also essential.

A documented thorough and comprehensive discussion with the patient and his or her family as part of the informed consent process is advised to help clarify postsurgical outcome expectations.

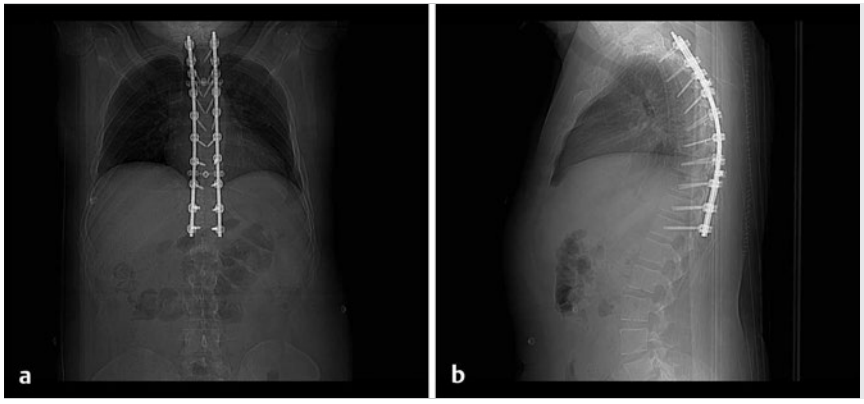

Fig. 111.1 (a, b) Initial postoperative radiographs showing good restoration of thoracic sagittal contour following kyphosis deformity correction.

111.7 Special Instructions, Positioning, and Anesthesia

The surgical treatment of sagittal alignment deformities resulting from junctional breakdown is highly dependent on the location of breakdown. In the upper thoracic spine, the anatomical structures make it difficult to approach anteriorly. Thus, posterior osteotomies are often necessary for deformity correction. In patients without rigid kyphosis or anterior ankylosis, Smith-Petersen osteotomy (SPO) or a Ponte osteotomy can be performed. Rib osteotomies may be considered following the previous posterior osteotomies if additional deformity correction is required. In this way, slightly more lordosis can be achieved. In the lumbar spine, a hybrid SPO + transforaminal lumbar interbody fusion (TLIF) can induce around 5 degrees additional deformity correction compared to a SPO alone. If more correction is required, a spinal canal shortening technique such as the pedicle subtraction osteotomy (PSO) may be used. Vertebral column resections are utilized when there is minimal to no sagittal curve flexibility. The techniques for the osteotomies are discussed elsewhere in the textbook. Spinal anchors (hooks, screws) can then be placed to pull the upper segment back into place.

For a lumbar or low thoracic junctional breakdown, correction of sagittal alignment may be performed via an anterior interbody approach. In patients with a significant deformity, correction of alignment may be necessary within the previous fusion. This requires a combined multistaged procedure such as a front, back, front or a back, front, back procedure. These specific techniques are discussed elsewhere.

In elderly or osteoporotic patients, prophylactic vertebroplasty may be preventative of future proximal junctional collapse.

111.8 Tips, Pearls, and Lessons Learned

- Many deformity correction patients may be asymptomatic and therefore should be followed clinically and radiographically over an extended period.
- The use of intraoperative manual reduction and cervical traction may enhance correction. Manual intraoperative reduction occurs through posterior translation and extension.
- Choosing the appropriate proximal level of fixation is paramount. This should coincide with the first neutral vertebra above the scoliotic segment to ensure that instrumentation will encompass the entire sagittal deformity.
- Fusions should be extended to adjacent segments with greater than 5 degrees of segmental kyphosis because this is believed to be the strongest risk factor for junctional kyphosis.
- Consider extending the fusion to adjacent segments when severe disk degeneration exists.
- Several nonadjacent posterior osteotomies can distribute the cord-level correction over multiple levels and can reduce the risk of a focal neurologic deficit following surgery.
- The surgical approach for treating junctional breakdown is dependent on the level. Posterior osteotomies are the mainstay of treatment for upper thoracic breakdown. An anterior, posterior, or combined approach for severe deformity may be utilized for lumbar or low thoracic junctional breakdown.
- During treatment of low thoracic and lumbar junctional kyphosis, the interspinous space (ligamentous complex) should be avoided to prevent sagittal decompensation in the future.
- For treating upper thoracic junctional breakdown in patients with a fused anterior column, consider a possible posterior vertebral resection or multiple-level Ponte osteotomies to achieve significant correction.
- The SPO can achieve around 10 degrees of sagittal plane correction
- The SPO is classically performed in the thoracic spine for treating a fixed sagittal plane imbalance. Multiple SPOs can be done throughout the thoracic region.
- The pedicle subtraction osteotomy can achieve 30 to 40 degrees of sagittal improvement
- The PSO is mainly used for sagittal deformity in the lumbar spine, and is classically performed at L2 or L3, ideally with > 12 cm of sagittal imbalance.
- The SPO is associated with lower morbidity than the PSO, but requires a mobile anterior column with intact disk(s).

111.9 Difficulties Encountered

When performing an SPO, one should be sure to remove bone uniformly through the vertebral body to produce a proportional correction of the sagittal deformity. Asymmetric closure will result if more bone is removed from one side than the other.

One should be careful when using osteotomies when there is a rotatory or scoliotic component. Following an SPO, the anterior column will tend to rotate towards the coronal convexity whereas the posterior elements will rotate towards the concave side. In a rotated segment, there is a tendency to shorten the concave side and lengthen the convexity, and overcorrection can result in decompensation. An alternative osteotomy such as a vertebral column resection or an asymmetric PSO is preferred for coronal imbalance, whereas a Smith-Petersen or Ponte osteotomy should ideally be performed in a neutral vertebral segment. The SPO or a symmetric PSO cannot correct a coronal deformity.

111.10 Key Procedural Steps

- The patient should be placed prone with some flexion of the hips and knees. Closure of the osteotomies is facilitated by extending the hips.
- Consider neurophysiological monitoring.
- Following the incision, subperiosteal dissection of the spinous process, laminae, and facet joints is performed at the appropriate level(s).
- Pedicle screws are placed in the upper thoracic spine (lateral mass screws for cervical) to the level of proximal instrumentation across the targeted sites.
- For a SPO Kerrison punches are utilized to resect a wedge of bone, starting centrally and working out laterally through the facet joints and pars.

- Osteotomies are used along with protection of the neural elements to perform a PSO. It is imperative to control blood loss aggressively throughout the procedure.
- A combined anterior and posterior approach with rib osteotomies and high thoracic vertebral column resection should be considered in patients with severe deformity that cannot be adequately corrected with the other surgical options.
- The osteotomies are closed employing a combination of applied compression and cantilever forces.

111.11 Bailout, Rescue, and Salvage Procedures

Adequate fixation is imperative for arthrodesis. Patients with osteoporotic bone often require additional levels of fixation to achieve the overall goals of surgery such as proper deformity correction and stabilization of decompressed motion segments.

Pitfalls

- The interspinous space at the adjacent level to a fusion limit should be avoided if possible.
- Poor patient selection (i.e., large salvage procedures in medically frail patients who cannot physiologically tolerate the necessary decompression and reconstruction). Many patients are asymptomatic and can be treated conservatively.
- Choosing the wrong osteotomy in the presence of severe deformity

112 Wound VAC Management for Spinal or Bone Graft Wound Infections

William Ryan Spiker

112.1 Description

Postoperative wound infections in spine surgery can occur at the surgical site or at the site for bone graft harvest (most commonly the anterior or posterior iliac crest). Regardless of the location of the infection, surgical eradication has often required multiple surgical débridements in addition to long-term intravenous antibiotics. This relatively common complication occurs in 1.9 to 20% of patients and poses a significant problem to both the patient and the surgeon. Traditional management with repeated débridements has largely been replaced by one or two operative débridements followed by placement of a wound vacuum-assisted closure (VAC) device (▶ Fig. 112.1). These closed-system suction systems are composed of sponges that are placed in the wound bed, an adhesive and occlusive dressing that keeps the sponge in place and provides a barrier to keep the negative pressure in the wound, and a vacuum device that can provide a range of negative pressures in either a constant or intermittent manner. Wound VAC systems have been used by general surgeons, neurosurgeons, and orthopaedic surgeons throughout the body and have been shown to remove interstitial fluid, improve blood supply, possibly decrease bacterial load, stimulate the proliferation of granulation tissue, decrease wound size, and improve time to healing.

112.2 Key Principles

Use of a wound VAC system facilitates management of surgical infections; however, general wound care principles must still be followed. Host factors such as blood sugar (fingerstick glucose levels perioperatively) and nutritional status (prealbumin) must be optimized. Whenever possible, antibiotics should be held until after cultures are obtained to ensure accurate results to guide appropriate antibiotic therapy. Operative débridement must include removal of all purulent fluid and sharp resection of necrotic tissue combined with low-pressure irrigation to

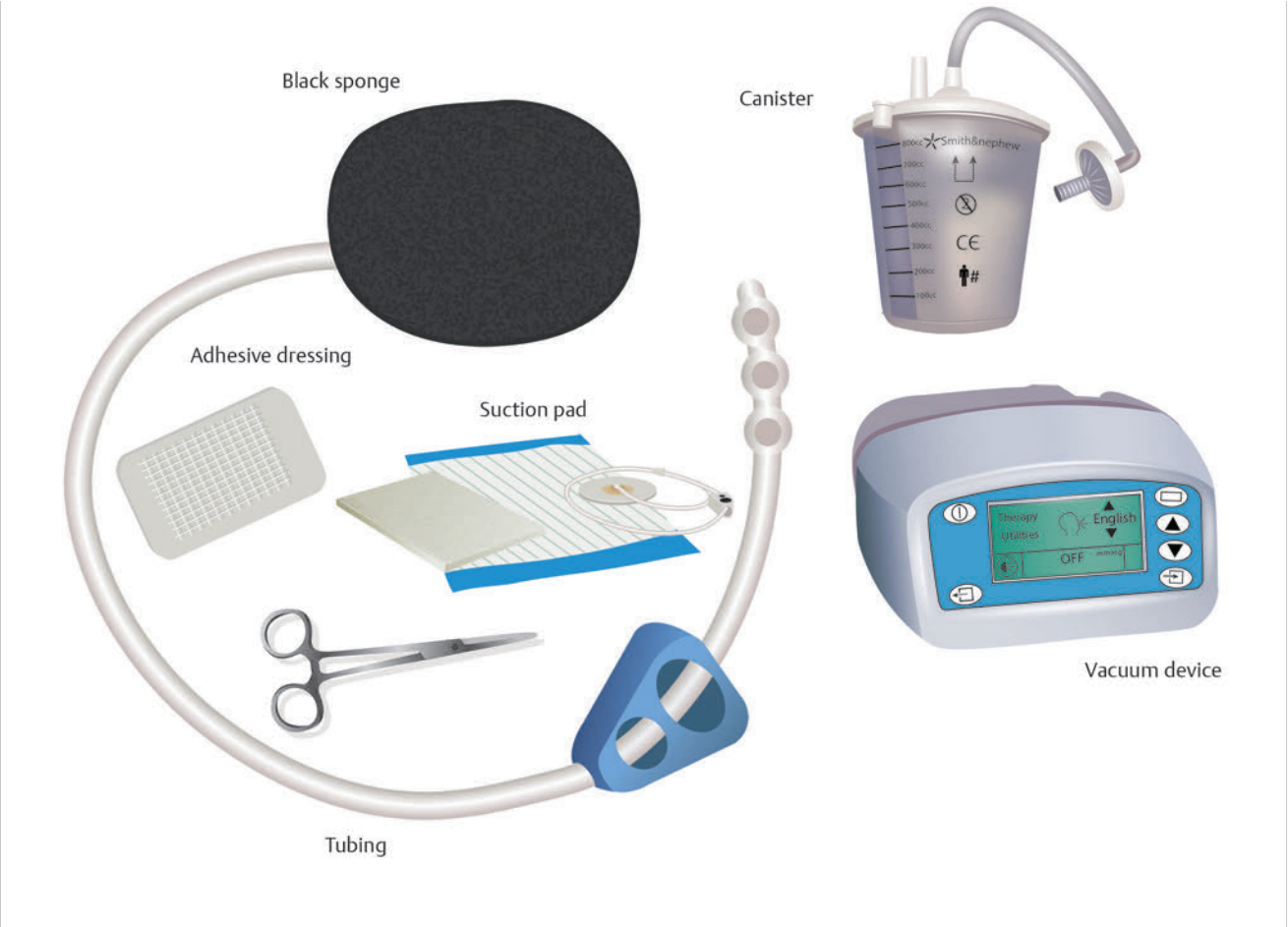

Fig. 112.1 This illustration shows the contents of a standard wound vacuum-assisted closure (VAC) kit, including the sponge, adhesive and occlusive dressing, tubing with suction pad, and vacuum device with canister.

decrease the bacterial load. In cases of severe or advanced infections, multiple débridements may be necessary to adequately prepare the surgical bed prior to placement of a wound VAC device.

112.3 Expectations

Use of wound VAC in patients with postoperative spinal infections is expected to encourage granulation tissue formation, shorten the time to healing, reduce the number of operations, and decrease the length of hospitalization. The wound VAC should only be placed after operative débridement has removed all gross purulence and necrotic tissue. The wound VAC device must be changed every 48 hours. Suprafascial wound VAC changes are commonly performed on the surgical floor with intravenous pain medication with or without local anesthetic by the surgical or nursing team. Deep wound VAC changes often require sedation and are usually performed in an intensive care unit or operating room (OR) by the surgical team. After the surgical bed begins to show healthy granulation tissue, closure can be expedited by operative closure with a local flap or skin grafting.

112.4 Indications

Wound VAC treatment is appropriate for postoperative spinal infections or iliac crest wound infections, after adequate surgical débridement and irrigation. De novo spinal infections can also be treated with a wound VAC after surgical débridement. Negative pressure devices are commonly set to a pressure of 125 mm Hg with intermittent suction, but can be adjusted based upon the clinical situation.

112.5 Contraindications

- Active cerebrospinal (CSF) leak: Use of a wound VAC system in this setting may predispose to a CSF leak or may remove large amounts of CSF leading to an uncal herniation.
- Closed infections: The wound VAC device cannot decompress abscesses or any other closed infections. Surgical débridement must occur prior to wound VAC device placement.
- History of dural tear or CSF leak that has been repaired (consider suprafascial low intermittent suction)
- Long-term steroid use with fragile skin

112.6 Special Considerations

Use of negative-pressure wound closure devices such as a wound VAC device in the spine can be complicated by exposed bone or exposed dura. The wound VAC sponge can be placed directly on exposed bone, but some animal studies have suggested that decortication encourages the formation of granulation tissue over the bone. Any necrotic bone must be removed prior to sponge placement. In the presence of exposed dura, it is important to use the appropriate wound VAC sponge and adjust the intensity of the negative pressure. A dense hydrophilic sponge, VAC vers-foam (white color) is nonadherent and should be used in the subfascial space. The reticulated hydrophobic GranuFoam (black color; Kinetic Concepts, Inc.) can then be placed superficial to the fascia to allow a relative suction gradient. When placing a sponge directly over the dura, the suction should be decreased to 75 to 100 mm Hg and reduced if the patient reports any radicular symptoms that may be due to excessive traction from negative pressure.

112.7 Special Instructions, Positioning, and Anesthesia

A few simple techniques can help decrease the pain associated with wound VAC changes performed outside of OR. Intravenous or oral pain medications should be given before the procedure, and the sponge should be moistened with saline and/or local anesthetic to allow easier removal. Any significant débridement should be performed under conscious sedation or in the OR.

112.8 Tips, Pearls, and Lessons Learned

Negative-pressure dressing systems depend on the sponge contacting the entire surface area of the wound to allow healing from the inside out. It is critically important for the sponge to cover the entire wound base and walls, including any tunneling or undermining that may have occurred. Failure to do so may allow premature closure of one of these pockets and creation of an abscess (**Video 112.1**). This may present itself as persistent fevers, increased pain, or persistently elevated inflammatory markers (e.g., erythrocyte sedimentation rate, C-reactive protein). If purulent material is encountered during a sponge exchange, further débridement should be performed until a clean wound bed is available for wound VAC sponge placement. Whenever possible, the wound should be packed with a single sponge of the appropriate size. If multiple sponges are used, this must be well documented to ensure that all sponges are removed at subsequent wound VAC changes.

112.9 Difficulties Encountered

Proper education of the nursing and surgical team members is crucial to ensure that the surgical wound is properly packed with sponge material at all wound VAC changes. Further, placement of sponge material over intact skin will lead to maceration and eventual skin loss and must be avoided. In complex wounds, placement of a hydrocolloid dressing (DuoDERM, ConvaTec) along the wound edge can adequately protect the underlying skin. For all wound VAC changes, a responsible care provider should be present to ensure that healing is progressing appropriately.

112.10 Key Procedural Steps

Operative débridement with irrigation should be performed until all purulent fluid and necrotic material has been removed from the surgical bed. Wound VAC placement is then commonly placed at the time of the last débridement. In a sterile environment, the sponge should be cut in the appropriate shape and

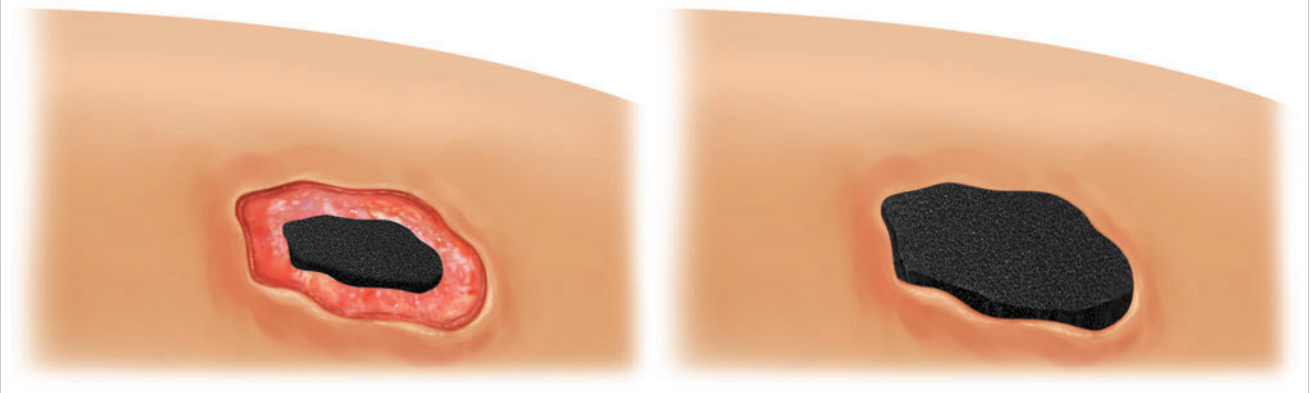

Fig. 112.2 This image shows appropriate sponge placement on the left and inappropriate placement on the right side. Failing to have the sponge contact all walls of the wound bed can lead to premature closure of parts of the wound and abscess formation.

size to match the wound with care to ensure that all walls of the wound are in contact with sponge. In the case of exposed dura, a hydrophilic sponge (white color) should be placed over the dura with the traditional hydrophobic sponge (black color) placed superficially. After the skin is thoroughly dried, the adherent and occlusive dressings are then placed over the sponge with care to ensure that the skin edges are not covered by the sponge. The occlusive dressing can be cut into strips and placed sequentially to simplify the process in large wounds. A small hole (~ 2.5 cm^2) is then cut in the center of the wound and is covered by the suction pad. To minimize pressure injury to the surrounding skin from the suction tubing, excess sponge material can be placed over the initial dressing and under the tubing along the patient's back and secured with the adhesive covering. Before contaminating the surgical field, suction should be applied and the leak rate tested to ensure that adequate suction can be maintained. The amount of suction and type of therapy (intermittent vs. constant) can then be selected to complete the procedure.

112.11 Bailout, Rescue, and Salvage Procedures

Failure of wound VAC management of postoperative spinal infections is rare and may be due to premature closure of parts of the wound bed leading to abscess formation or persistent bacteremia with repeated seeding of the surgical site. Regardless, persistent infection requires repeated débridements and new cultures to ensure appropriate antibiotic coverage. Silver-impregnated wound VAC sponges or saline wet–dry daily dressing changes may be beneficial. Hardware removal is rarely necessary.

Pitfalls

- Premature placement of a wound VAC sponge in a wound with purulence or necrotic material and failure to adequately fill the wound bed with sponge material are common causes of failed Wound VAC therapy (▶ Fig. 112.2).
- Placement of a wound VAC sponge over a CSF leak can lead to pseudomeningocele formation or frank uncal herniation and must be avoided.

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Note: Page numbers set **bold** or *italic* indicate headings or figures, respectively.

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